LA-UR-22-20518

Approved for public release; distribution is unlimited.

Title: IHE DDT Qualification Tests FY20-FY21

Author(s): Holmes, Matthew David; Lopez-Pulliam, Ian Daniel; Broilo, Robert M.; Erickson, Michael Andrew Englert; Parker, Gary Robert Jr.; Heatwole, Eric Mann; Feagin, Trevor Alexander; Trujillo, Daniel J.

Intended for: Report

Issued: 2022-01-21

Los Alamos
NATIONAL LABORATORY

IHE DDT Qualification Tests FY20-FY21

Holmes, Matthew D.
Lopez-Pulliam, Ian D.
Broilo, Robert M.
Englert-Erickson, Michael A.
Parker, Gary R.
Heatwole, Eric M.
Feagin, Trevor A.
Trujillo, Daniel J.

Los Alamos National Laboratory
M-6 Explosives Applications and Special Projects
High Explosives Thermal and Mechanical Response Team

December 20, 2021

Abstract

A DDT tube test was designed to meet all requirements established in the new DOE IHE qualification standard. Ten tests were successfully executed with PBX 9502 as a demonstration of the design, assembly, heating system, and methods, and to establish a baseline set of test results with an existing IHE. The explosive response in all tests was low violence (as anticipated). This report contains detailed design drawings, assembly instructions and procedures for future execution of the qualification test series, and makes recommendations for minor improvements.

Table of Contents

Figures

1. Introduction

PBX 9502 is classified as an Insensitive High Explosive (IHE). A new qualification standard for IHE compositions[1] was developed 2013-2021 jointly by LANL, LLNL, and SNL (Appendix A). The new standard was enacted with an interim determination memo by the DOE in 2016 (Appendix B) and was added to the 2019 version of the DOE Explosive Safety Standard[2].

This new standard established a series of high-level test requirements for an energetic material to be considered an IHE. However, the qualification standard even in its final form does not specify the precise design and procedure that is required for practical implementation of the testing. This leaves some flexibility for the details of test execution.

In this report, we document a bespoke test design that was created to satisfy the DDT tube portion of the new qualification standard. We report the results of four DDT tube tests executed with PBX 9502 from 2020 – 2021 using this design. We justify design choices and explain the motivations underlying the qualification standard. The test design, control systems, and diagnostics are documented in detail.

2. IHE Qualification Motivation

The DOE defines an IHE composition in Chapter IX of the *DOE Explosive Safety Standard* (most recent version: DOE-STD-1212-2012)[3] as follows:

> "IHE Materials are mass-detonable explosives that are so insensitive that the probability of accidental initiation or transition from burning to detonation is negligible."

The DOE is the authority responsible for the safety and security of the nuclear arsenal; as such, the DOE definition of IHE is informed primarily by concerns for nuclear safety. The position of the DOE is that the only way in which either an inadvertent nuclear detonation (IND) or an aerosolized dispersal of nuclear material can occur is if the high explosive experiences a mass detonation. A low order reaction of the explosive, i.e. deflagration, is of insufficient violence to cause IND or aerosolized nuclear dispersal. Therefore, for the primary DOE concern of avoiding IND, an IHE is most usefully defined as an explosive that, when subjected to an accidental insult, will not result in a mass detonation.

Note that a distinction is made between an IHE "material" and an IHE "subassembly". A sufficiently insensitive explosive composition can qualify as an IHE material. Provision is further established for a subassembly that contains non-IHE explosive material, but the geometry and attributes of the subassembly convey additional safety sufficient to qualify the specific assembly an "IHE subassembly". Both the IHE material and subassembly qualifications are addressed in the new standard. In this report we focus exclusively on the material qualification.

Historically, the weapons establishment has recognized only TATB and TATB/Kel-F compositions as IHE materials. This includes the LANL composition PBX 9502 (95% TATB, 5% Kel-F 800) and the LLNL composition LX-17 (92.5% TATB, 7.5% Kel-F 800). The qualification of TATB as an IHE was established in 1983, and no new IHE has been qualified since. However, there has been a resurgence of interest in the past two decades with qualifying new explosive formulations as IHEs[4-6].

The rekindled interest in IHE qualification motivated a review of the original qualification standard. A new IHE qualification standard was developed jointly by Los Alamos National Laboratory (LANL) and Lawrence Livermore National Laboratory (LLNL) and first issued as a draft in 2016 as a joint report titled *IHE Material and IHE Subassembly Qualification Test Description and Criteria* [1]. On August 29, 2018 a memorandum was issued by the NNSA which established the aforementioned report as the new IHE qualification standard until such time as it can be incorporated into the DOE Safety Standard [7]. In 2021 the draft was edited into a final version and approved by the laboratories[1]. The new IHE qualification standard identifies the underlying principles that drive explosive sensitivity, and establishes a reduced series of tests which target the relevant explosive properties.

The old qualification standard for an IHE consisted of a diverse series of historic tests [8] and was lacking in numerous regards. The historic tests that constituted the IHE qualification standard were not purpose-designed for assessing the suitability of an explosive as an IHE. Rather, the tests were borrowed from existing experiments that assessed diverse and often irrelevant properties of the explosive. The testing suite employed disparate apparatuses that were available at the time, and analysis of results was rooted in experience and empirical observations. While the suite of tests successfully established the insensitivity of TATB, it did so with redundancy and wasted effort, and most importantly, none of the tests directly addressed the need that the IHE have a negligible likelihood for deflagration-to-detonation transition (DDT). In many cases it is unclear what explosive property the old test was measuring or why that measurement matters. This is reflective of the limited knowledge that persisted at the time regarding the underlying principles that govern explosives safety. It has long been the case that explosive detonation properties are quite well understood, while sub-detonative phenomena remain less studied.

The body of knowledge regarding the factors that dominate explosive violence has improved dramatically since 1983. Phenomenologically, research has proceeded from opposite ends to meet in the middle. On one end, research has started with specific accident insult scenarios—e.g. a fuel fire or a bullet impact—and proceeded to identify ignition mechanisms and explosive phenomena associated with those specific insults. From the other direction, research has started with the mechanisms and phenomena, and proceeded to identify the relevant accident scenarios that might produce these phenomena. Collectively the improved understanding has clarified the definition of "insensitive" within the explosives community, and ultimately informed the choice of tests to constitute the new IHE qualification standard.

The "sensitivity" of an explosive can be divided into two distinct categories:

1) Shock sensitivity: if a shock impulse is delivered to the explosive, what pressure and duration of impulse is required to *initiate* a *detonation* in the explosive? This shock sensitivity is nicely quantified with a "Pop-plot", which is a log-log plot of pressure vs. distance for initiation[9]. Obviously, an explosive cannot qualify as insensitive if it is *overly* shock sensitive. However, perhaps surprisingly, the shock sensitivity of an explosive is not ultimately the most challenging hurdle for an explosive to qualify as an IHE.

2) Propensity to DDT: if a non-shock insult is delivered to the explosive, does it cause an *ignition* of a *deflagration,* and does that deflagration then transition to a detonation? This process—the deflagration-to-detonation transition—has been studied for decades. However, a rigorous predictive capability has yet to be developed, and so the propensity for a particular composition to undergo DDT must be tested empirically. With very few exceptions, an accidental insult does not lead directly to *initiation* of *detonation* in the explosive. Accidental impacts of the explosive, even bullet impacts of the explosive, do not generally lead to a prompt SDT (shock-to-detonation transition) detonation of the explosive. Rather, accidental insults lead to *ignitions* of a *deflagration.* However, via pressure-building processes, a deflagration can amplify in violence to end in a detonation. By this reasoning, the propensity for a composition to DDT is the most important consideration when assessing explosive response to accidental stimuli.

The newly written IHE qualification standard includes four tests: an SDT test (addressing sensitivity issue #1 above), a DDT test (addressing issue #2 above), a Skid Test, and a Bullet test. In this report we address only the DDT test portion of the IHE qualification standard.

3. Background Knowledge

3.1. PBX 9502 Thermal Response Background

Much work has been done in the past decade to develop a cookoff model for PBX 9502 that predicts the location and time-to-cookoff for a charge subjected to a fuel-fire scenario (i.e. slow cookoff), primarily at LANL and SNL[10-15]. The results from these studies informed the choice of thermal boundary conditions that were proscribed in the new qualification standard for the DDT test.

Effort has also been expended to research the permeability and gas transport properties of PBX 9502 at elevated temperatures, and the relevance to cookoff behavior[16-18]. It was found that PBX 9502 remains highly impermeable up through the point of self-ignition, and the impermeability may be a factor contributing to low post-ignition violence.

3.2. DDT Background

The deflagration-to-detonation transition has been studied for decades, and signification progress has been made[19,20]. Sufficient knowledge exists to identify the key variables that dominate DDT behavior, and to identify a set of conservative experiment conditions to guide the design of a DDT qualification test.

3.2.1. Confinement

Confinement is one of the primary variables contributing to the propensity for DDT to occur. Consider that PBX 9501, a conventional high explosive (CHE) has never been observed to DDT in the absence of confinement. We define "confinement" as any aspect of the configuration that may act to restrict the dynamic gas flow that occurs during rapid reaction. Restricting the gas flow serves to amplify the pressure attained before disassembly occurs; increased pressure increased the ultimate violence.

We commonly refer to two different forms of confinement: *mechanical* and *inertial*. *Mechanical* confinement consists of an external vessel, containing the explosive, that possesses strength. Explosive reaction acts to expand the vessel; the vessel strength inhibits gas escape. *Inertial* confinement consists of any material "in the way", i.e. mass that needs to be accelerated during the explosive reaction in order to provide expansion room for product gases. Inertial confinement can refer to the mass of vessel walls, but also to the mass of the explosive itself. Consider a scenario in which a large bare (not contained in a vessel) explosive charge is centrally ignited—the product gases from that central ignition expand against the outer explosive material—the reaction is inertially confined.

A charge contained in a thick steel-walled vessel experiences both mechanical confinement (the steel has strength) and inertial confinement (the steel is heavy). Steel has a wide range of properties depending on alloy and heat treatment. Superficially, it may seem as if the yield strength of the material is the only important parameter—i.e. stronger steel provides greater confinement. However, increasing the yield strength of a steel typically also increases brittleness and reduces ductility. Consider a steel with a very high yield strength but with little strain-to-failure (it's brittle). Such a steel may briefly contain high pressure, but rapidly fail with extensive brittle fracturing. The fracturing opens vent paths, effectively eliminating the confinement. Contrast this with a more ductile steel, which begins to yield early but stretches substantially without fracturing, effectively containing the reaction for a longer duration. "Toughness" is the trait that captures the combined optimization of ultimate yield strength and strain-to-failure, and may be a more relevant measure of confinement. These considerations are clearly relevant when assessing the confinement provided by a steel vessel, and a qualitative understanding of how the material attributes contribute to violence guides experimentation. However, at the present time the "worst-case" combination of steel attributes that would maximize reaction violence has not been quantified. For this reason, we design an "over-test" that has greater confinement by a large margin.

3.2.2. Size

DDT is a building process that begins with burning at a low rate. As material reacts and pressure increases, so does the burn rate until a shock is formed. A consequence of this progression is that the whole process requires both a sufficient quantity of HE and adequate time for the process to complete. The time element is covered in the previous section where the necessary condition of confinement is discussed. Equally important is the charge size. There must be enough HE to burn and build pressure up to the formation of a shock, as well as enough HE to undergo shock-to-detonation transition (SDT). The length needed for DDT to complete (aka DDT Run Length, or l^*) is the sum of the lengths of HE consumed in the slow initial burn, the intermediate-rate burn modes and the SDT length, which all vary as a function of pressure, HE chemistry and porosity. DDT is precluded in charges smaller than the DDT Run Length. In keeping with the over-test objectives of the IHE DDT Qualification Test, it becomes necessary to ensure the size of the DDT test charge is greater in any dimension than any practical system, so that size is not a process-limiting factor.

3.2.3. Thermal Damage

Explosives subjected to elevated temperatures can undergo various changes that increase the likelihood of DDT; taken together these changes constitute "thermal damage". We will use the substantial amount of elevated thermal research conducted with the conventional high explosive PBX 9501 to guide the thermal damage discussion. In the case of PBX 9501, elevated temperatures have three primary negative effects[20]:

1) Thermal expansion creates interconnected porosity.

2) Binder softens, migrates, and decomposes, and HMX begins decomposition, leaving additional porosity.

3) A crystalline phase change occurs in the HMX, from $\beta \rightarrow \delta$ (beta- to delta-). The delta phase exhibits increased shock sensitivity. Moreover, the phase change process is responsible for additional thermal expansion and crystal fracture.

Unlike PBX 9501, PBX 9502 does not exhibit a phase change on the path to ignition, and the Kel-F binder in PBX 9502 is thermally stable up to the ignition temperatures of TATB. These differences contribute to the comparative insensitivity of PBX 9502. There is some evidence for high-temperature decomposition chemistry of TATB, producing furazans moieties and water. There is also evidence that PBX 9502 becomes more sensitive to weaker shocks at elevated temperature, and because the DDT process involves strengthening shock formation prior to detonation, shock sensitization would naturally increase propensity for the transition.

When dealing with new, prospective IHE candidates, our knowledge of the factors that exacerbate DDT in PBX 9501 guide our design of a conservative test configuration. For this reason, the new qualification standard requires the DDT testing to be performed in such a way that encourages thermal damage to develop prior to ignition.

4. DDT Qualification Test Design

In this section we discuss the entire design for the test, including the high-level philosophy driving the design attributes already proscribed in the new qualification standard as well as the additional design choices that are required in order to build and execute the test ITRW (in the real world).

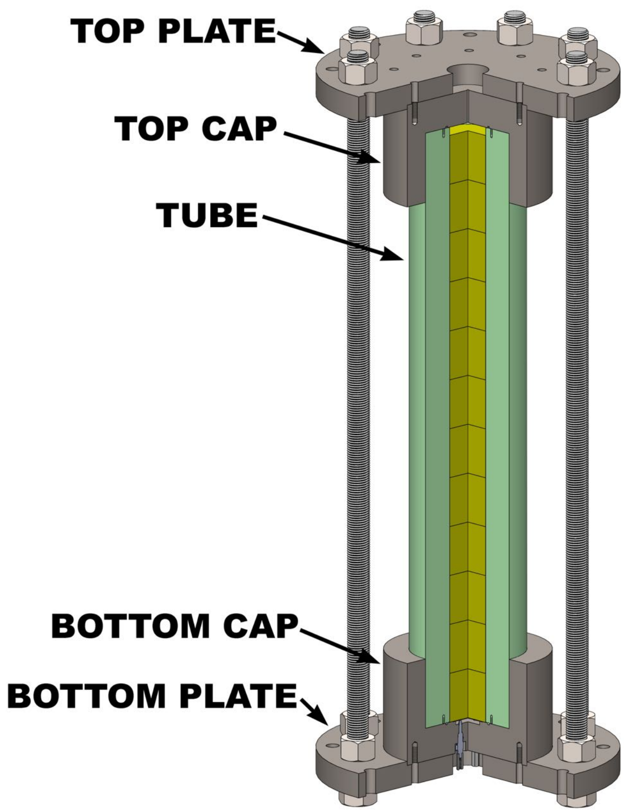


Figure 1. Diagram identifying the primary vessel parts.

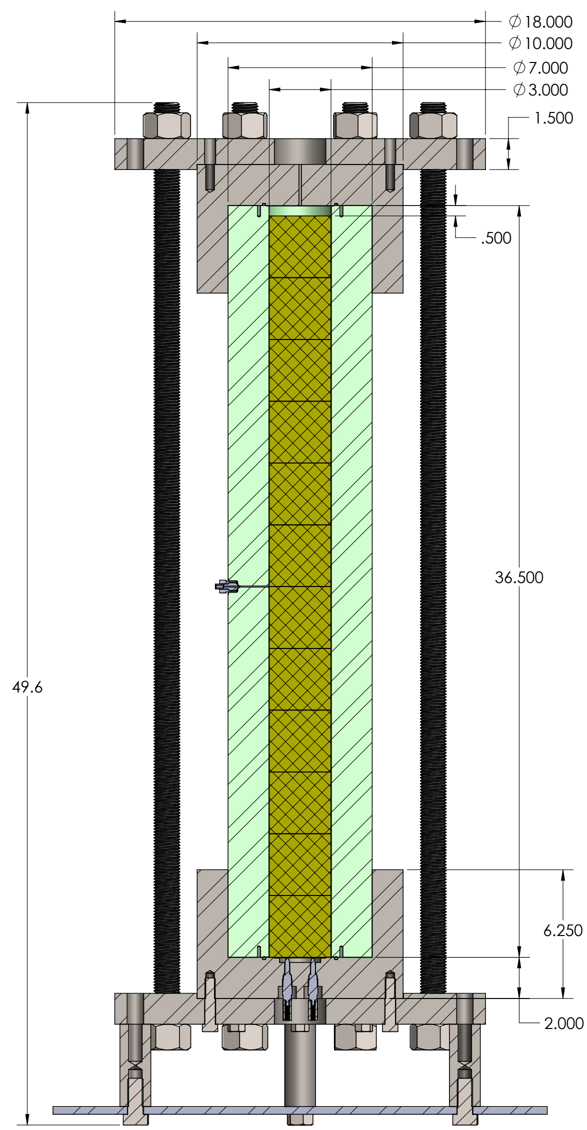


Figure 2. Cross-section drawing showing the primary dimensions relevant to confinement design, in inches.

4.1. Vessel

Figure 1 shows a labelled diagram of the central tube components.

The qualification standard specifies that confinement of the explosive shall be a minimum of 2-inch wall thickness of steel on the sides, top, and bottom of the tube. This results in an outer tube diameter of 7 inches.

Our design uses a "belt and braces" approach, whereby the end-caps of the tube are both threaded and clamped. Two caps are used on each end. The first set of caps screws onto the tube (as in a "pipe bomb"). The second set of caps clamps the tube lengthwise with threaded rod that runs the length of the tube.

It is difficult to determine which steel alloy is most conducive to causing DDT. A mild steel yields at a lower stress, but is more ductile so that it maintains a gas seal to greater strains before failure. A hardened steel has a much higher ultimate strength, but fractures at low strains. The optimal combination of strength vs. toughness to promote DDT has not been determined. The qualification standard specifies "yield strength of the steel to be ~36 ksi (or larger)" and that it "should be widely-available commercially."[1] This yield strength requirement is easily satisfied by most steel alloys. In this way, experimenters may select from numerous commonly available, economical steel alloys that exceed the minimum tensile strength requirement. For our design we chose hot-rolled 1018 steel tube with a yield strength of 41.2 ksi for the tube and end-caps components, and hot-rolled A36 steel plate with a yield strength of 50 ksi for the clamping plates (note that the nominal yield strength for A36 is considerably lower than 50 ksi, however our particular batch of steel was tested and the material certification is documented in Appendix G). Both of these are inexpensive, readily available, easily machined industry standard mild steels.

The tube is designed over-long, such that a gap remains at the top of the tube after it is filled with consolidated pellets. This provides ullage for thermal expansion to permit porosity to develop. Substantial evidence suggests that the increased porosity associated with thermal expansion exacerbates the cookoff violence for HMX-based compositions[20]. Porosity increases the shock sensitivity which accelerates the final stage of DDT; this underlying sensitization mechanism should hold true regardless the energetic. If space is not provided for expansion to occur, the evolution of porosity can be suppressed. In the interest of making this a conservative worst-case test, we accommodate thermal expansion with this design.

The ideal amount of ullage to maximize thermal expansion is composition-dependent. However, altering tube length for every prospective composition is incompatible with the goals of establishing a simple, standardized test (it would require a research effort exploring thermal expansion). For the standard, an ullage was selected based on PBX 9502, for which sufficient data exist to make an informed choice[21]. The ullage permits maximum thermal expansion while still ensuring that all ullage is consumed by expansion by the time ignition occurs (if excess ullage is provided, it reduces confinement during the dynamic pressure-building event).

The tube is deliberately vented to be leaky to quasi-static pressure changes during thermal conditioning, in order to provide a practically achievable uniform test condition. If the tube were gas tight, it would be necessary to provide both a leak-rate and static pressure-rating criteria to be used for the qualification test, so that testing performed by different institutions would give repeatable results. Matching an identical leak-rate and pressure-rating with disparate test apparatus and conditions is impractical. The deliberate venting provides an achievable uniformity for the qualification standard.

However, the leak path is specified to be a small diameter hole (0.125 inches), such that the tube is essentially sealed during the dynamic event as the hole experiences choked flow. Additionally, the hole is located on the end of the tube opposite the ignition location, so that it is maximally separated (spatially and temporally) from the initial post-ignition response. It is anticipated that this deliberate leak path contributes negligibly to pressure relief during a sufficiently violent post-ignition reaction (the only way the small diameter hole *can* provide a relevant leak path during the post-ignition reaction is if the post-ignition reaction is so benign that gas evolution is insufficient to generate a violent explosion).

The presence of the leak path may affect the time that ignition occurs. It has been shown that PBX 9502 will ignite earlier if the confinement is sealed rather than vented [11]. However, the differing time-to-ignition as a result of the quasi-static gas seal has not been observed to affect the post-ignition violence, and is therefore not a relevant factor for the propensity of a composition to undergo DDT.

4.2. Explosive

There are two considerations for selecting a tube diameter for a DDT test: failure diameter of the explosive, and the characteristic length scale in a real weapon.

In a column of detonating explosive, it is well known that insufficient diameter can cause a decay and failure of the detonation, due to pressure release waves at the boundary[22,23]. PBX 9501 is considered an "ideal" explosive and the critical diameter is reported to be 1.52 mm [24]. However, less sensitive explosives are often "non-ideal" and possess a larger critical diameter—large enough that detonation front curvature and thus edge-losses become non-negligible at the scale relevant for a main charge. PBX 9502 has a critical diameter of 7-9 mm at 20 ˚C [25,24]. If a column of unconfined PBX 9502 with a diameter less than ≈8 mm is deliberately detonated, the detonation decays and ultimately fails. Note that critical diameter is stated here for unconfined charges. Confinement provides a high impedance boundary which reduces the critical diameter of energetic needed to sustain detonation. In this way, the presence of a steel-walled tube further increases the conservatism of the test with regard to critical diameter.

The diameter of the explosive column in the qualification standard is 3 inches, to be conservative with respect to the critical diameter and relevant dimensions of prospective IHE candidate materials. From experience, pellets can be uniaxially pressed by our explosive machining group within +0.010 inches tolerance (without requiring additional machining). Consequently we chose a bore diameter in the tube of 3.020 inches. This provided adequate clearance for inserting the explosive pellets with provision for slightly oversized pellets, as well as thermal expansion/contraction without being so oversized as to provide excess ullage. For additional information on the coefficient of thermal expansion of PBX 9502 please consult reference [21].

The PBX 9502 used for the consolidated pressed cylinders originates as prills from Holston® lot HOL88H891-009 (colloquially referred to as "Dev lot 9"). Cylinders 3 in. diameter x 3 in. height were uniaxially pressed by the LANL explosive machining group to a nominal density of 1.89 g/cc (Appendix K). Each pellet has a nominal mass of 658 g. One shot requires 12 pellets, for a nominal shot mass of 7.9 kg. For the first shot with PBX 9502 prills, the prills were sourced from lot 64-034 which was formulated by Philip Leonard in the M-7 group at LANL. All other prills shots used Dev lot 9 material. When prills were used, 2465 g (≈5.4 lb) were required to fill the tube (bulk density of the filled tube was 0.575 g/cc).

4.3. Run length

It has been shown in DDT tube experiments that a certain length of reaction propagation is required before DDT is observed, even with conventional high explosives. In PBX 9501, run-lengths of 2-9 cm are typical in thermally damaged and pre-heated material [20]. For less sensitive materials, provision must be made for considerably longer run lengths. However, weapons systems do not contain infinite lengths of explosive—above some conservative threshold length it becomes irrelevant for the purposes of weapons safety whether an explosive can DDT.

The length of the explosive column in the qualification standard is specified as 36 inches, to be conservative with respect to run-length.

4.4. Ignition System

Reliability is the primary consideration for a DDT tube ignition system. PBX 9502 burns poorly; it is necessary to provide an intense thermal source to achieve a reliable ignition.

We use two standard diesel engine glow-plugs as a safe, reliable, easily mounted thermo-electric source to ignite a thermite mixture. The glow plug is Bosch® model 80010 (Appendix N). Each glow plug has a nominal resistance of 0.8 Ω at ambient temperature. The second glow plug is for redundancy, in the unlikely case that one burns out. The glow plugs are wired in parallel to a DC power supply (BK Precision® model 9115). The nominal voltage supply to the glow plugs is 14.4V. However, the length and gauge of the connecting wires and the quality of the connections will introduce additional resistance into the system and this must be compensated for by increasing the supply voltage. The increase in voltage is determined empirically as follows. A pair of test glow plugs is wired up, using the final cabling configuration (but without any explosive on the mound). The voltage drop across the glow plugs is monitored, and the power supply voltage increased, until the voltage drop across the glow plugs is 14.4 V. It is possible to heat the glow plugs more rapidly using excessive voltage; in our experience this can lead to glow plug failure (burning out) and is not recommended. A 14.4 V drop across the glow plugs reliably ignites the thermite. To prevent premature damage to the ignitor system, we limited power supply current to 40 A.

Two layers of control are established for the DC power supply, for a redundant safety mechanism to prevent power from being inadvertently applied to the glow plugs. First, the DC power supply itself is powered through a relay that is remotely actuated over the optical fiber connection (the remote relay system was custom-built in-house). Second, the operation of the DC power supply is controlled using a Labview VI serial interface connected via USB, and this laptop is accessed via remote desktop over the network connection.

The thermite used in the experiments is a stoichiometric mixture of aluminum (Al) and iron II,III oxide Fe_3O_4. The aluminum is in powdered form, sourced from Valimet® as their H-5 product. The H-5 aluminum is characterized by Valimet using Microtrac equipment to have a particle distribution as follows: 90% <15 µm, 50% <8 µm, 10% <4 µm. The iron oxide is procured as powder from Alfa Aesar, product 12374-A7. This product is sieved through a No. 325 mesh (by the manufacturer) which yields a maximum particle size of 44 µm. These powders are mixed using a LabRAM™ acoustic mixer in a weight % ratio of 3.22:1 iron oxide to aluminum (this is the stoichiometric ratio). The chemical reaction is:

$$3\mathrm{Fe_3O_4(s)}+8\mathrm{Al(s)} \xrightarrow{\Delta H=-3.677\frac{kJ}{g}} 9\mathrm{Fe(s)} + 4\mathrm{Al_2O_3(s)}$$

Note when modeling the heat evolved from this reaction, that 3.298 kJ/g reaction heat is released from solid reactants to liquid products, and the last 0.379 kJ/g is released as the molten reactants solidify.

Approximately 17 g of thermite was required to fill the pocket in the End Cap (15.8 g and 19 g were used in Test 3 and 4, respectively), which results in a bulk density of 1.5 g/cc (this is highly variable depending on thermite compaction).

4.5. Heating System

The heating rate specified by the standard—20 ˚C/hr—prevents this test from being completed in a standard work day. For PBX 9502, the heating time was approximately 12 hours. As the shot is heated, personnel are not permitted to enter the clearance. If personnel are sheltering inside a bunker, they are not permitted to exit the bunker during this unsafe period. The inability to escape the bunker for a ~12 hour duration makes it untenable to remain in the bunker during the test. Consequently, the entire experiment must be remotely conducted, including heating control, ignition, diagnostics, data collection, and surveillance. Much of the complexity of the system is driven by the need for safe, reliable remote control.

It is desirable to heat the entire column of explosive uniformly. The qualification standard specified that the external temperature measurements will remain within 10 ˚C along the length of the tube. We use Chromalox® brand ceramic band heaters, for high-temperature and high-power capability (Appendix M). Four of model CB7A6A1P2 were used on the central tube section, with 7-inch ID, 6-inch width, nominally 5000 W each at 240 V (40 W/in^2 power density). Four of model CB10A3A1P1 were used on the end caps (two on each), with 10-inch ID, 3-inch width, nominally 2400 W each at 240 V (26 W/in^2). We employed five control zones: top cap, tube top, tube middle, tube bottom and bottom cap (Table 1 and Figure 3). Differing power can be applied to the separate zones to maintain a more even spatial temperature profile along the length of the tube.

Lower power heaters could be utilized; however, below a certain power threshold (which will depend on the ambient wind and temperature at the experiment site) insulation would need to be added to the assembly in order to maintain the specified ramp rate and temperatures. Typically, insulation obscures diagnostics such as high-speed video and PDV probes. Excess heater power negates these issues and permits a linear heating ramp to the highest setpoint temperature.

The facility power available at the firing site is 480V three-phase. We purchased an off-the-shelf UL-listed commercially available transformer (Larson® model MPD-480-75K-200BE-120-208-C-W with 75 KVA capacity) to supply 208 V, 5-wire (wye-connected) to a power distribution unit ("PDU", Motion Laboratories® model 1300-200A-09-2-01), the output of which is five separate channels each of three-phase 208 V through L21-30R receptacles. Each power channel on the PDU supplies one of five custom-built relay boxes; each relay box controls one of the five zones. Each relay box has one DB9 female connector for digital inputs and one DB9 male connector for analog outputs (for monitoring voltage and current). A National Instruments® cDAQ-9188 chassis is used for interfacing with the relay boxes; NI-9475 modules are used for the digital outputs to the relay boxes, NI-9205 modules are used for analog inputs from the relay boxes. A connector junction box is used to adapt connections from the chassis modules to the relay boxes. The test may result in a violent reaction while power is being supplied to the heaters, exposing thermocouple conductors to voltages that can destroy equipment. For this reason, a separate cDAQ-9188 chassis, not connected to earth ground (floating), with NI-9214 modules is used for thermocouple connections. Additional details on the setup are available in Appendix H.

Table 1. Contains heater zone details. See also Figure 3 for zone locations.

Zone	Location	Quantity	Heater Width	Phases	Resistances Measured at Power Supply (Test #3 values)
1	top cap	2	3"	A-B, B-C	23.8 Ω, 23.9 Ω
2	top of tube	1	6"	C-A	11.5 Ω
3	Middle - straddling feedthrough	2	6"	A-B-B-C	11.5 Ω, 11.5 Ω
4	bottom of tube	1	6"	C-A	11.5 Ω
5	bottom cap	2	3"	A-B, B-C	23.8 Ω, 23.8 Ω

A custom Labview VI was built for precise, reliable heating control. It is a bespoke product that evolved over years of thermal testing. Notes on our system design, as well as the Labview VI software, are available on request. However, it should be noted that the qualification test can be successfully performed with a less precise, off-the-shelf control system, provided it maintains an adequate uniformity of temperature across the outside surface of the tube. The heating system was tested and tuned on an empty assembly. These test heatings provide a cooling curve to be used for calculating the wait time required before approach, in the event that diagnostics become disabled (Figure 5).

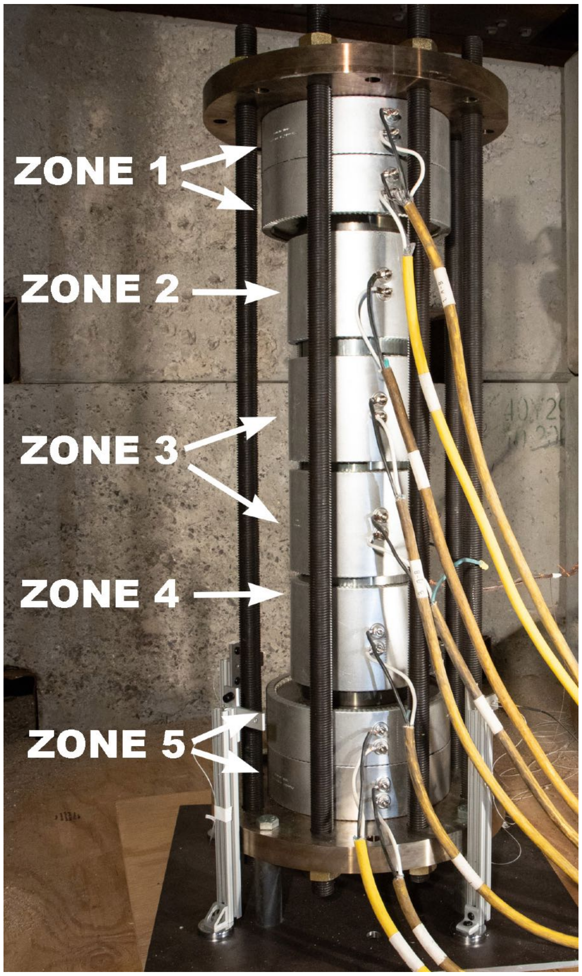


Figure 3. Illustration of zone arrangement of heaters.

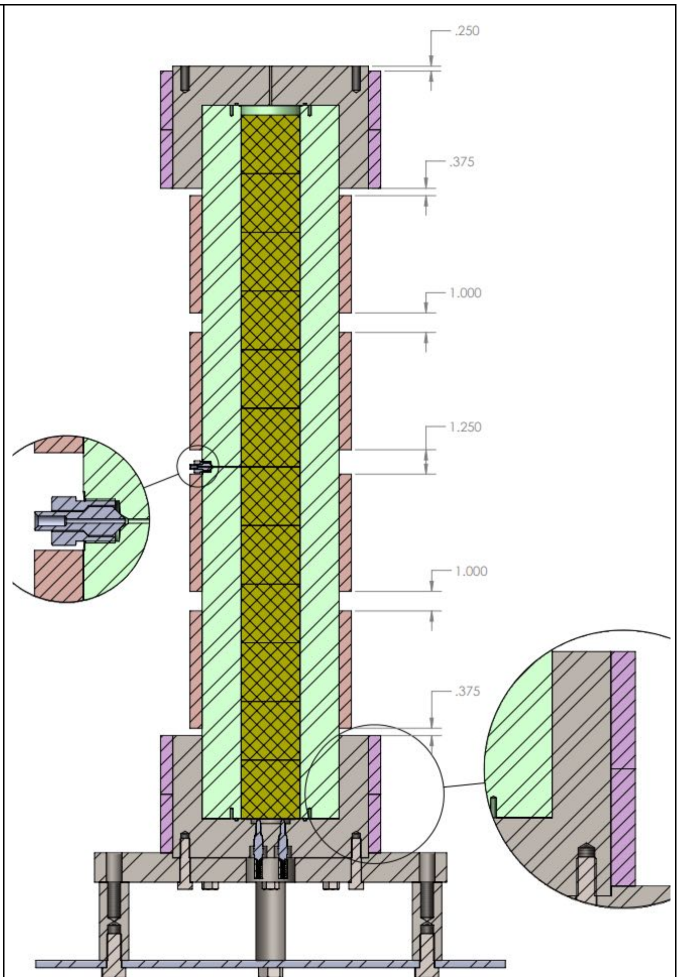


Figure 4. Cross-section drawing showing the positioning of heaters.

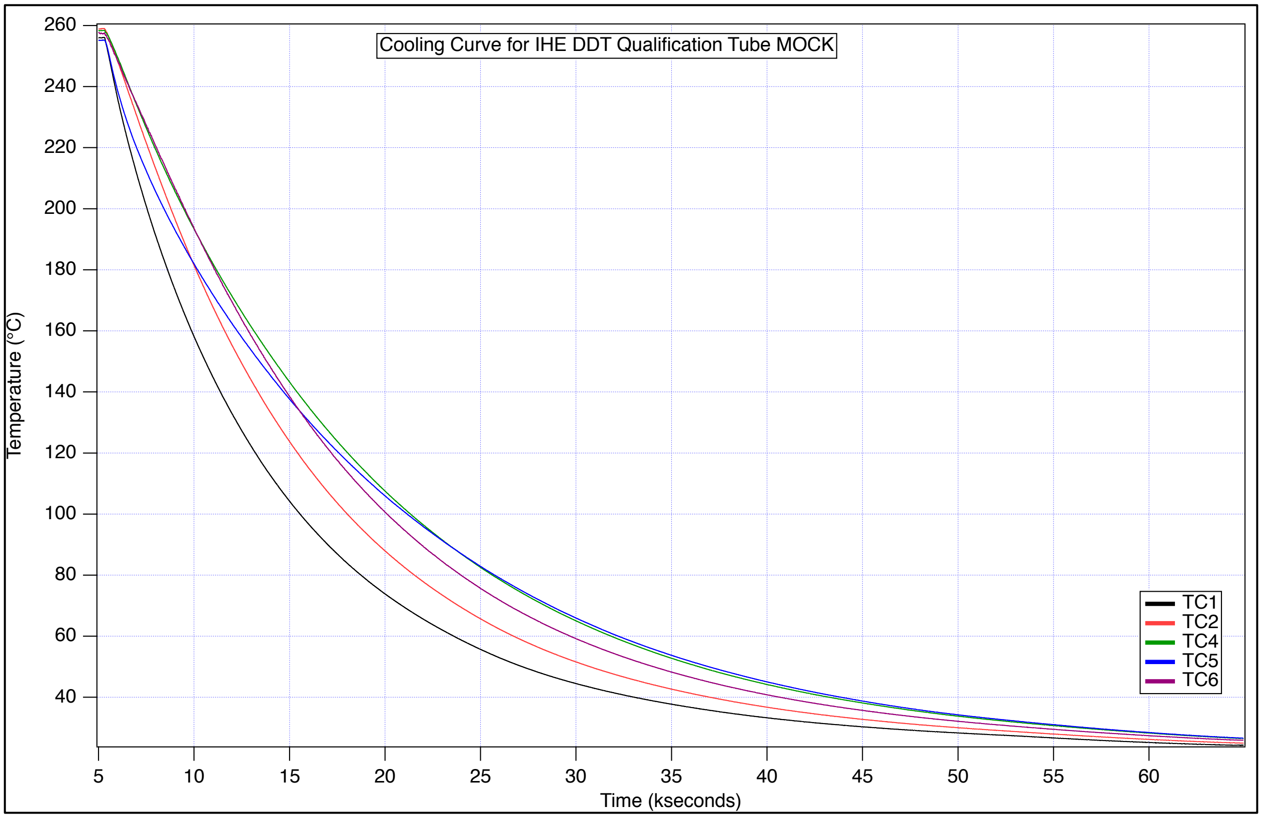


Figure 5. Cooling curve for a mock apparatus (empty). This test was performed indoors (ambient temperature 20 °C, windspeed 0). All thermocouples shown here are on external cylinder surface (no internal thermocouples were fielded for this tuning test).

4.6. Diagnostics

4.6.1. Thermocouples

Thermocouples (Omega® model 5SRTC-GG-K-36-72) were taped to the exterior surface of the tube. Locations are identified in Figure 9. They were electrically insulated from the tube using one layer of polyimide tape, and attached with a second layer of polyimide tape (Figure 6). Two layers of foil-backed fiberglass insulation were placed, foil-side facing the tube. Squares of stainless-steel shim stock 2.5-inch square, 0.010-inch thick were placed over the TC/insulation assembly, and held in place by the heaters. This arrangement ensures that the thermocouple is accurately recording the temperature of the surface of the steel and is not being cooled by convective air currents.

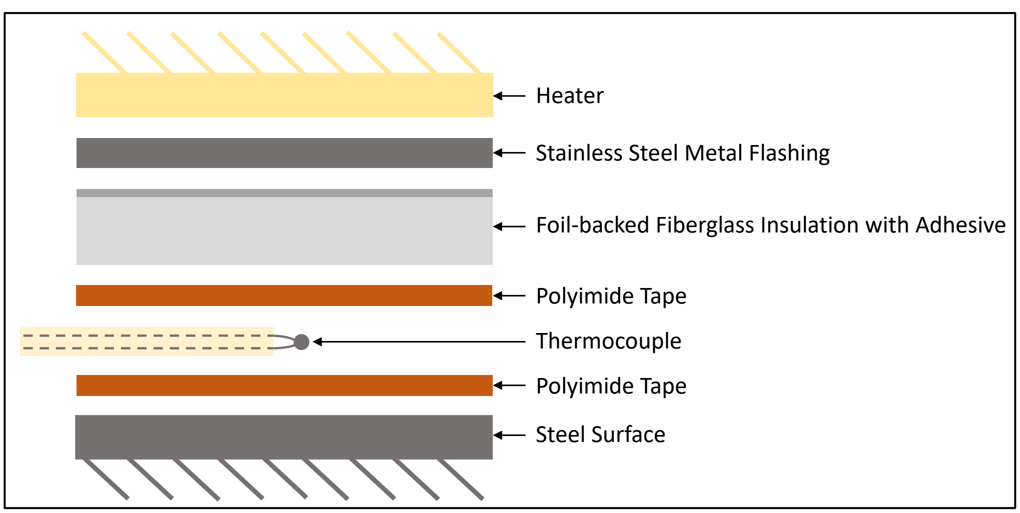


Figure 6. Diagram of thermocouple installation, including layering of polyimide tape and insulation.

The qualification test is a "go/no-go" test that requires minimal diagnostics. This was the intent of the authors of the standard, so that institutions across the complex could field this test identically, without requiring complicated, time consuming, difficult to replicate diagnostics. However, additional diagnostics, though not required by the standard, are also not forbidden. We elected to add interior thermocouples to the assembly, using a brazed high-pressure feedthrough that has been successfully utilized in the past. Omega® thermocouples with flexible metal probe tips 4 ft long 0.020-inch diameter were used (part TJC36-CASS-020U-12-SMPW-M[a]). An Autoclave Engineers pressure fitting was used, with a modified plug (a counterbore cavity was drilled to hold braze material). The probe ends were inserted through a custom drilled plug. The required length for probes to protrude was determined using the drawings. Probe lengths were adjusted as necessary and then brazed in place with high-strength braze alloy (56% silver/22% copper/17% zinc/5% tin with melt temperature of 1140-1200 ˚F). This feedthrough assembly is shown in Figure 7 and Figure 8.

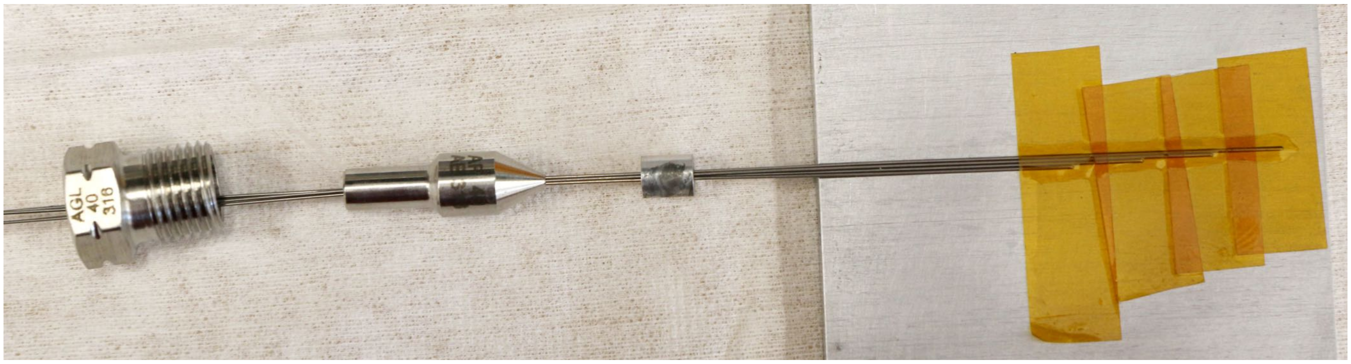


Figure 7. Thermocouple feedthrough with metal-sheathed TCs inserted to proscribed depth prior to brazing.

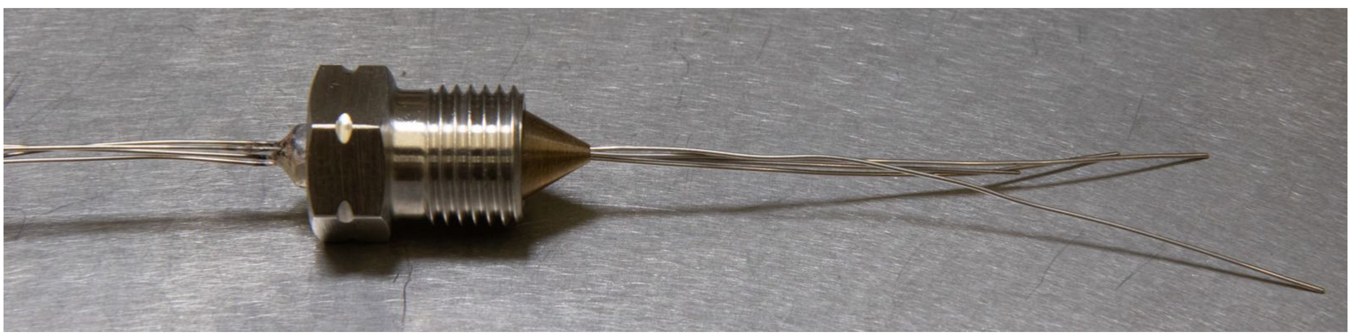


Figure 8. Feedthrough brazed, with nut in position for installation.

[a] This thermocouple has a 12-inch long probe, with stainless-steel sheath, and the bead is ungrounded. For future experiments, a better choice would be a) SuperOmegaCladXL™ sheath material as it sustains higher temperature which assists in creating a good brazing joint without melting the probes b) a grounded tip as the grounded tip responds to temperature changes more rapidly. The part number for this better choice is TJC36-CAXL-020G-12-SMPW-M.

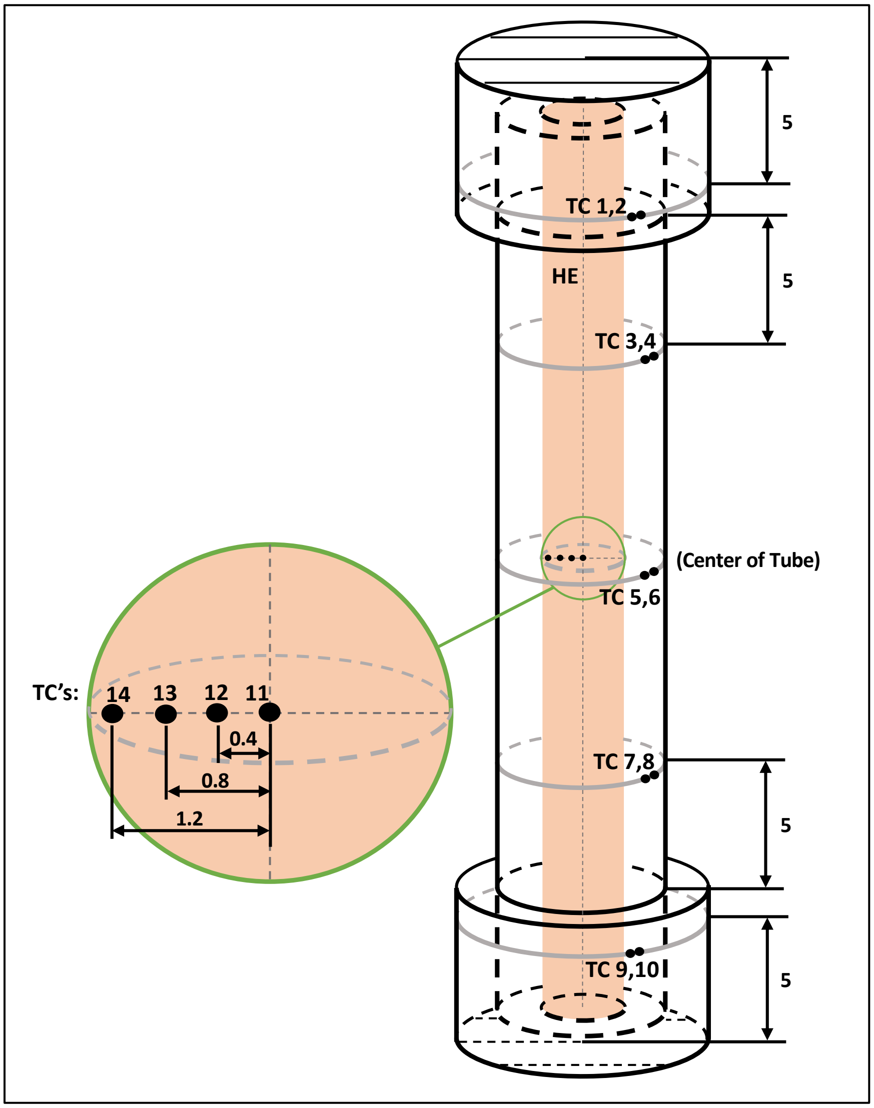


Figure 9. Thermocouple locations.

4.6.2. Post-mortem Fragment Analysis

A detonation in consolidated PBX 9502 produces pressures in a steel vessel that greatly exceed the failure stress, resulting in thorough fracturing of the steel to fragments that are approximately as wide as thick. The thickness of the case determines the characteristic size of fragments resulting from detonation. Fragmentation theory can be used to estimate size distribution[26].

The situation is not as clear-cut when dealing with pour density prills of PBX 9502. The pressures produced in a detonation through this very low bulk-density material may be insufficient to cause "complete" fracture of the case—i.e. with fragments approximately as wide as they are thick. We performed purposeful detonation of both consolidated pellets and pour-density prills in representative sections of tube to obtain baseline results. This characterizes the fragment morphology for a "known" detonation and can be compared to the ignited experiments to help determine if detonation occurs.

4.6.3. High-speed video

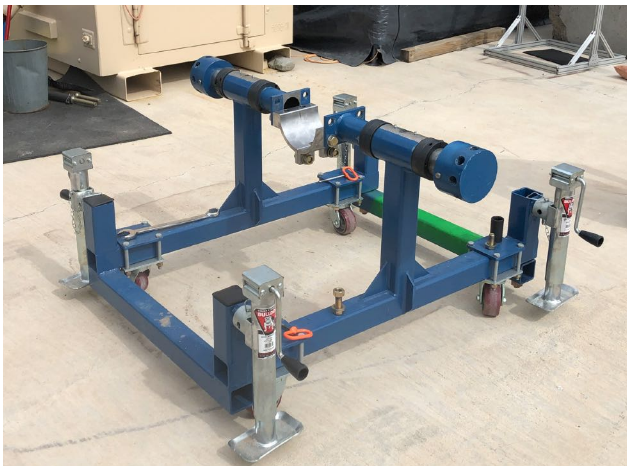
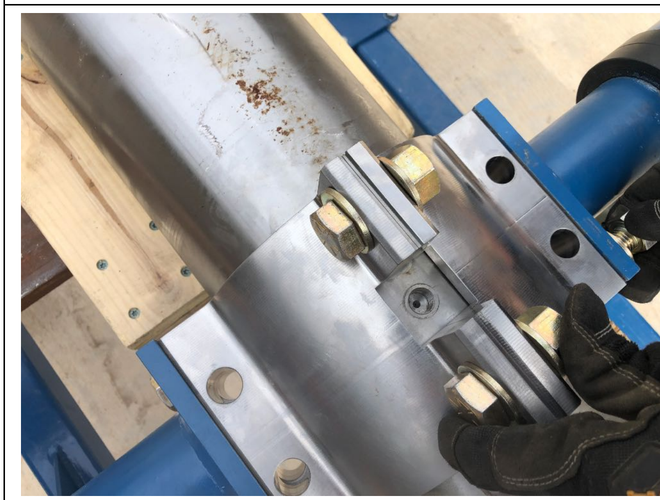
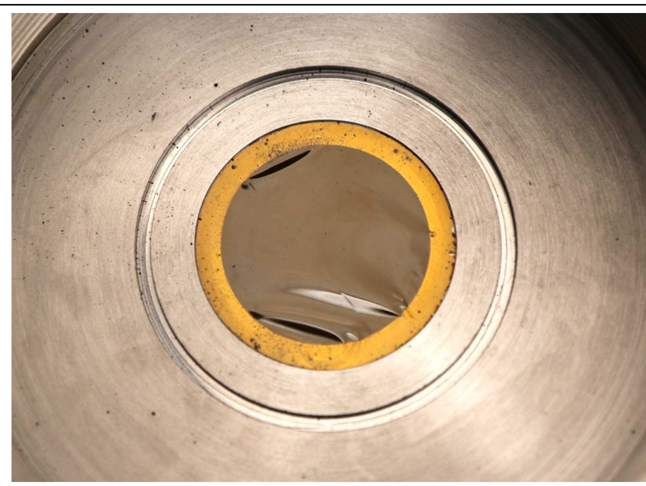
Video was captured using a Phantom® V2512 high-speed video camera with a 896 px wide by 800 px tall window using a 100-400 mm zoom lens at 180 mm focal length, aperture f/5.0, at 6,000-20,000 frames/s (frame rate was adjusted on a test-by-test basis to adjust exposure to accommodate available illumination). At these frame rates, the camera record duration is 8-23 s. Triggering is accomplished using a piezoelectric contact pin, or manually via software as a backup in the event that the piezo pin isn't impacted hard enough to provide a trigger.

5. Assembly

A detailed assembly procedure is provided in Appendix C. The tube apparatus consists of many heavy parts which poses challenges for safe assembly and transport. The end plates weigh 94 lb each, the end caps weigh 92 lb each, and the tube itself weighs 324 lb. The total weight of the apparatus, assembled, is approximately 800 lb.

In order to safely assemble the apparatus, a stand was built that permits rotation of the tube for assembly, and provides rolled transport for insertion into the pre-assembled block house on the firing site.

Table 2. Assembly photos.

 **Figure 10. Stand with lower cradle half mounted, ready to accept tube.**	 **Figure 11. Forklift used to lower tube into cradle.**
 **Figure 12. View of tube feedthrough lined up with square cutouts in clamping parts.**	 **Figure 13. Thermite pocket in bottom cap, filled and covered with Kapton tape.**

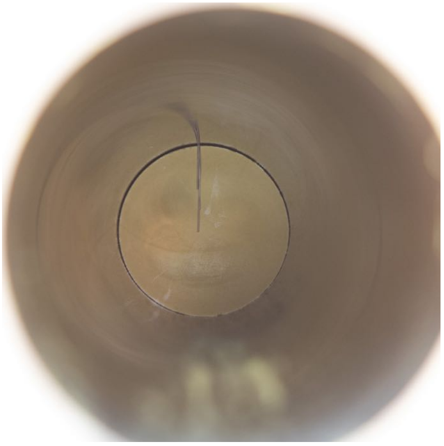


Figure 14. View down tube of thermocouples inserted at midplane, after half the pellets have been inserted.

Figure 15. Tube fully loaded with explosive.

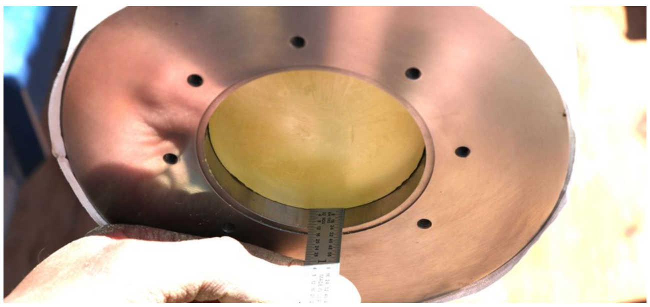


Figure 16. Detail of ullage remaining after final pellet is inserted.

Figure 17. Top of tube taped with Kapton barrier. A hole is poked in center of tape to provide vent path.

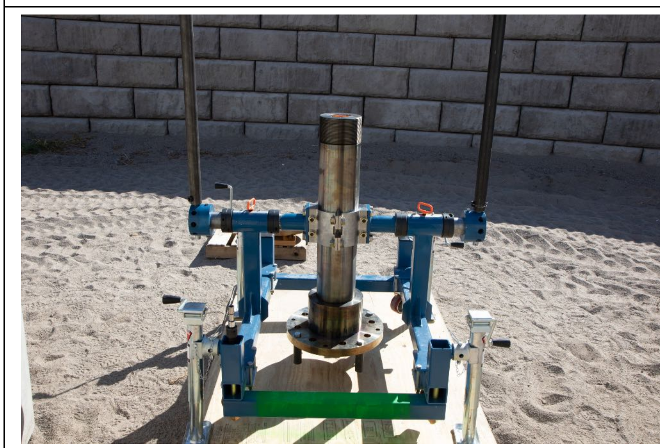


Figure 18. Tube is full of explosive and has been rotated vertically for installation of the end cap.

Figure 19. End cap installed.

Figure 20. Tube has been placed in blockhouse. Heaters are being installed.

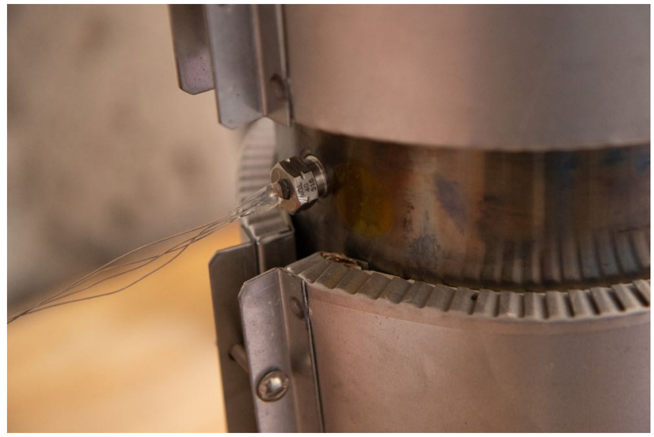


Figure 21. Detail view of the thermocouple feedthrough at the midplane.

Figure 22. Overview of blockhouse from the outside.

Figure 23. Point of view from the video camera porthole, showing the arrangement of turning mirrors for viewing the shot.

Figure 24. View of large turning mirror in alleyway of blockhouse.

Figure 25. Shot with heaters installed and wired.

Figure 26. View of block house from behind.

Figure 27. Another view of block house.

Figure 28. Zoomed perspective of the turning mirror's view of the shot.

Figure 29. Shot illuminated in the dark at 11 PM prior to starting heating.

Figure 30. Back of the shot.

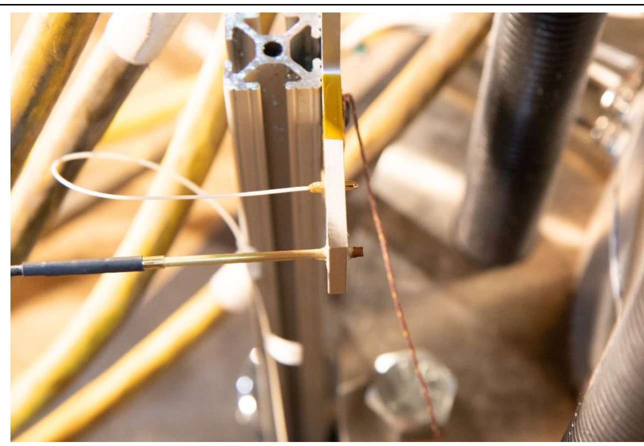


Figure 31. Detail view of the PDV probe and piezo pin mounting system. PDV was fielded on the first shot only.

6. Test Matrix

The qualification standard calls for 9 tests to be performed, with the potential for 2 additional detonation calibration tests. There are five unique versions of the experiment specified in the qualification standard (some of which require identical repeats); these test conditions are shown in Table 3, identified with a "Test ID" of 'A' through 'E'. The tests that were actually conducted in our test series and reported in this document are shown in the test matrix in Table 4.

Table 3. Unique tests required per the qualification standard.

Test ID	Material State	Thermal Profile	Ignition Method	Notes
A	consolidated, production density	heated at 20 ˚C/hr	self-ignition (cookoff)	this is a slowly heated test which serves to identify a conservatively low temperature threshold at which the material will self-ignite (cookoff); the temperature is designated Tc (critical temperature[b])
B	consolidated, production density	heated at 20 ˚C/hr to 10 ˚C below T_c	end ignited	the thermal profile is designed to maximize thermal damage while avoiding self-ignition; deliberate end ignition provides the longest run-distance available for DDT to occur (a cookoff typically occurs in the center, which halves the available run-distance)
C	molding prills, pour density	heated at 20 ˚C/hr to 10 ˚C below T_c	end ignited	This is the same as above, but with molding prills instead of consolidated pellets.
D	consolidated pellets	none	deliberately detonated	This is a shortened, 10-inch tube, deliberately detonated to provide a baseline result for diagnosing detonation by postmortem fragment analysis.
E	molding prills, pour density	none	deliberately detonated	This is a shortened, 10-inch tube, deliberately detonated to provide a baseline result for diagnosing detonation by postmortem fragment analysis.

Table 4. Test matrix follows qualification standard. Tests 9 and 10 are necessary for comparison if violence approaches high-order result. The red-highlighted row identifies a test that is listed in the qualification standard matrix, but was not completed.

Test #	Test ID	Test execution date (start)	HE source	HE mass	Material State	Thermal Profile	Ignition Method
1	A	11:13 AM 6/24/2020	HOL88H891-009; BC80388; TOR3321; 19-176-31 thru -42	7896 g ± 10 g	consolidated, production density	heated at 20 ˚C/hr	self-ignition (cookoff)
2	A	10:53 AM 7/15/2020	HOL88H891-009; BC80386; TOR, 19-176-1 thru -12	7896 g ± 10 g	consolidated, production density (1st repeat of test 1)	heated at 20 ˚C/hr	self-ignition (cookoff)
3	B	11:11 AM 8/5/2020	HOL88H891-009; BC80386, -88, -92; TOR3321, 19-176-31 thru -42, 19-176-43 thru -45, 19-176-91 thru -96	7896 g ± 10 g	consolidated, production density	heated at 20 ˚C/hr to 10 ˚C below T_c	end ignited
4	C	10:04 AM 8/13/2020	Philip Leonard BC#91773	2465 g ± 10 g	molding prills, pour density	heated at 20 ˚C/hr to 10 ˚C below T_c	end ignited
5	B	11:10 AM 3/29/2021	Dev Lot 9	7896 g	consolidated, production density (1st repeat of Test #3)	heated at 20 ˚C/hr to 10 ˚C below T_c	end ignited (bottom ignition)
6	C	9:45 AM 4/7/2021	Dev Lot 9	3248 g	molding prills, pour density (1st repeat of Test #4)	heated at 20 ˚C/hr to 10 ˚C below T_c	end ignited (bottom ignition)
7	C	8:55 AM 4/15/2021	Dev Lot 9	3373 g	molding prills, pour density (2nd repeat of Test #4)	heated at 20 ˚C/hr to 10 ˚C below T_c	end ignited (bottom ignition)
8	B	9:15 AM 4/22/2021	Dev Lot 9	7896 g	consolidated, production density (2nd repeat of Test #3)	heated at 20 ˚C/hr to 10 ˚C below T_c	end ignited (bottom ignition)
9	E	12:52 PM 4/29/2021	Dev Lot 9 (897.5 g PBX 9502, 519 g C-4, RP-83 detonator)	1418 g total	molding prills, pour density	none	deliberately detonated
10	D	4:26 PM 4/29/2021	Dev Lot 9 (2199 g PBX 9502, 519 g C-4, RP-83 detonator)	2720 g total	consolidated pellets	none	deliberately detonated

[b] We define a "critical temperature" within the context of this particular test. This "critical temperature" is not to be confused with other uses of the term, for example in the Henkin small-scale safety test.

Since the first test is used to identify a critical temperature, it is most sensible to perform the repeats of that test immediately, before continuing with the other variations, so that those tests can be averaged to establish a defensible critical temperature (T_c) for use in the future variations.

Tests 10 and 11 are necessary if there is any ambiguity in the test results regarding the lack of a detonation. If the results from any of the first nine tests are violent—potentially high-order—then tests 10 and 11 serve as baseline tests for comparison.

7. Results

7.1. Test 1 Results

Test 1 was successfully ramped at 20 ˚C/hr until cookoff (Figure 59). The explosive cooked off when the setpoint was 273.2 ˚C (Figure 60), 44,200 s (≈12.3 hrs) after the start of the test. The internal thermocouples showed evidence of self-heating; highest internal temperature recorded was 281.6 ˚C on TC13. This suggests that the cookoff location was near to the midplane, where the thermocouples were measuring, but not exactly at the thermocouples (if the cookoff occurred precisely at a thermocouple location, we would expect to see temperatures in the 300-350 ˚C range before disassembly). This is an anticipated outcome: the longitudinal temperature gradient is deliberately minimized in order to uniformly damage the entire column of explosive, consequently we would expect the ignition location to occur somewhere along the central axis.

Frames extracted from the high-speed video record are shown in Figure 32. The first sign of reaction consists of yellowish ejecta streaming out the top vent hole. Next, the threads on the bottom cap are stripped and the cap is pushed downward relative to the tube. In the process, the top and bottom plates are dished outward, and the portion of all-thread protruding above the top cap and below the bottom cap are bent outward. These features are visible in the images. The gap that is opened around the bottom threads is sufficient to vent pressure, and the contents of the tube burn without further deforming the assembly. Hot gases escape in the gap around/past the failed bottom threads, and stream upward along the surface of the tube. The gases strip off the bottom few heaters, and in the act of demolishing the heaters flames become visible as the internal heating elements are exposed to the high-velocity product gases. The force of the venting gas causes the assembly to fall over in the block-house, coming to rest up leaning up against the concrete wall. The experiment does not fully disassemble during the reaction. To enable disassembly—so that the inside of the tube can be accessed after the test—the all-thread rods need to be cut. The dishing deformation of the end plates caused them to pinch the edge of the cap, bonding the two parts.

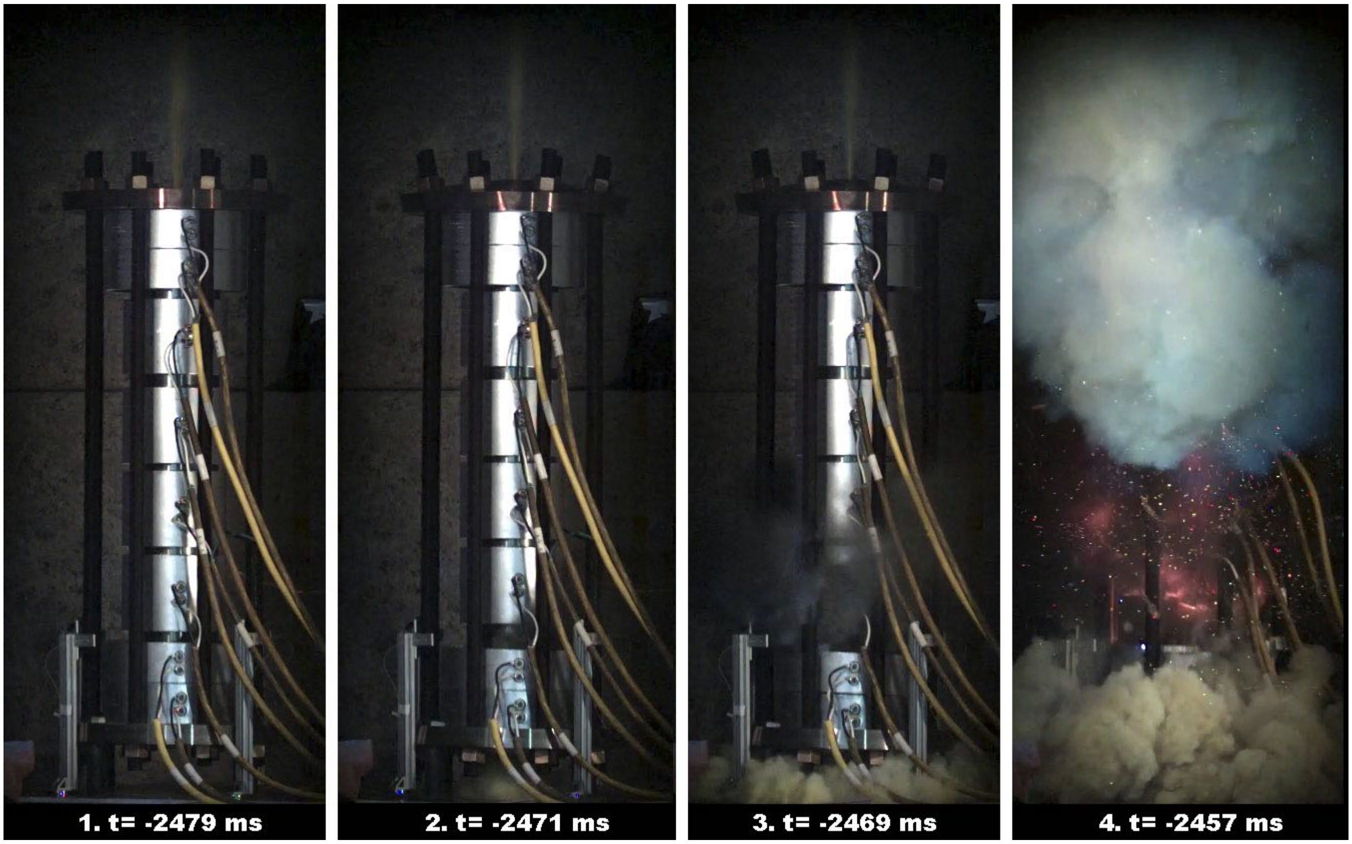


Figure 32. Test 1. Frames extracted from high-speed video record. In frame 1, ejecta is already visible streaming out of the top vent hole, but the assembly shows no other signs of reaction. In frame 2, smoke/debris is visible below the bottom plate as well as in the region between the bottom cap and tube. The bottom and top plates are visibly deforming. In frame 4, high-velocity gases are jetting out of the failed cap-tube threads, traveling upwards and stripping the heaters off; the visible flames occur when gases interact with the internal heating elements.

This result is best described as a deflagration; a pressure-burst; a low-order response. Violence was quite low, nowhere close to a detonation. The test was such low-violence that it failed to impact the piezo pin for triggering purposes. Instead, the high-speed video was triggered manually when the reaction was remoted observed on the surveillance cameras.

The response for this test was typical of all subsequent tests. In all tests reported here, either the top or bottom cap stripped the threads and partially slid off the tube end, providing a vent path to mitigate reaction rate. None of them fully dismantled; all had to be cut apart.

After each test, *before* disassembling the tube, the experiment was remotely “kill-cooked” in order to eliminate any residual explosive (and the concomitant explosive hazards). This involved heating the experiment well above the reaction temperature for PBX 9502 (up to 400 ˚C for example) and leaving it there for sufficient duration to ensure that no explosive could possibly have survived. Once the explosive hazards have been eliminated, the shot can be safely approached even when hot (the burn hazard from the hot metal remains). However, we typically let the entire shot cool overnight as a matter of course before approaching it for removal/disassembly.

7.2. Test 2 Results

This test cooked off when the setpoint was 269.9 ˚C, 42,864 s (11.9 hr) after the start of the test. The highest temperature recorded before disassembly was 296.5 ˚C on TC14.

The assembly for Test 2 started ≈4 ˚C warmer than Test 1 due to ambient conditions, so it reached temperature slightly sooner. In Figure 63 the start time for the Test 2 was adjusted to synchronize the experiments to a temperature of 32.4 ˚C. After sychronization, the difference in cookoff times between the two experiments was 526 s (8.77 min). Based on a total test duration of 42,864, this represents a timing difference of only 1.2%, which constitutes remarkable repeatability.

As per the qualification standard, the critical temperature is defined per the qualification standard to be cookoff temperature less 10˚. The cookoff setpoint for Tests 1 (273.2 ˚C) and 2 (269.9 ˚C) were averaged to obtain a critical temperature (T_c) of 272 ˚C. Subsequent tests were end-ignited when the boundary temperature reached T_c-10 ˚C = 262 ˚C.

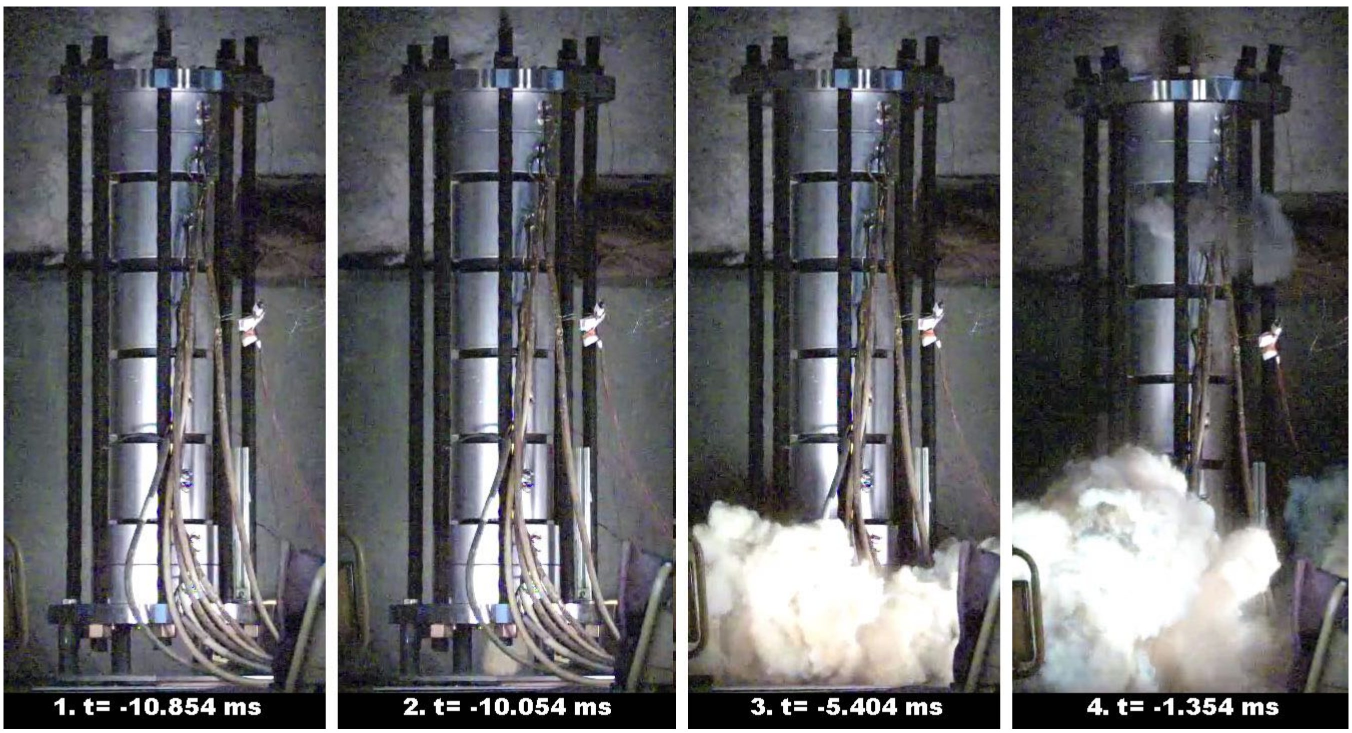


Figure 33. Test 2. Reaction is first visible as ejecta out bottom glow plug ports in frame 2. Eventually, top cap threads fail; this is visible in frame 4.

7.3. Test 3 Results

The thermal profile is shown in Figure 64, with a detailed view around ignition in Figure 65. The test was end-ignited when the boundary temperature reached 262 ˚C; at this point, the internal thermocouples were reporting an explosive temperature of 257 ˚C at the coldest (central TC) and 262 ˚C at the edge of the explosive (closest to boundary).

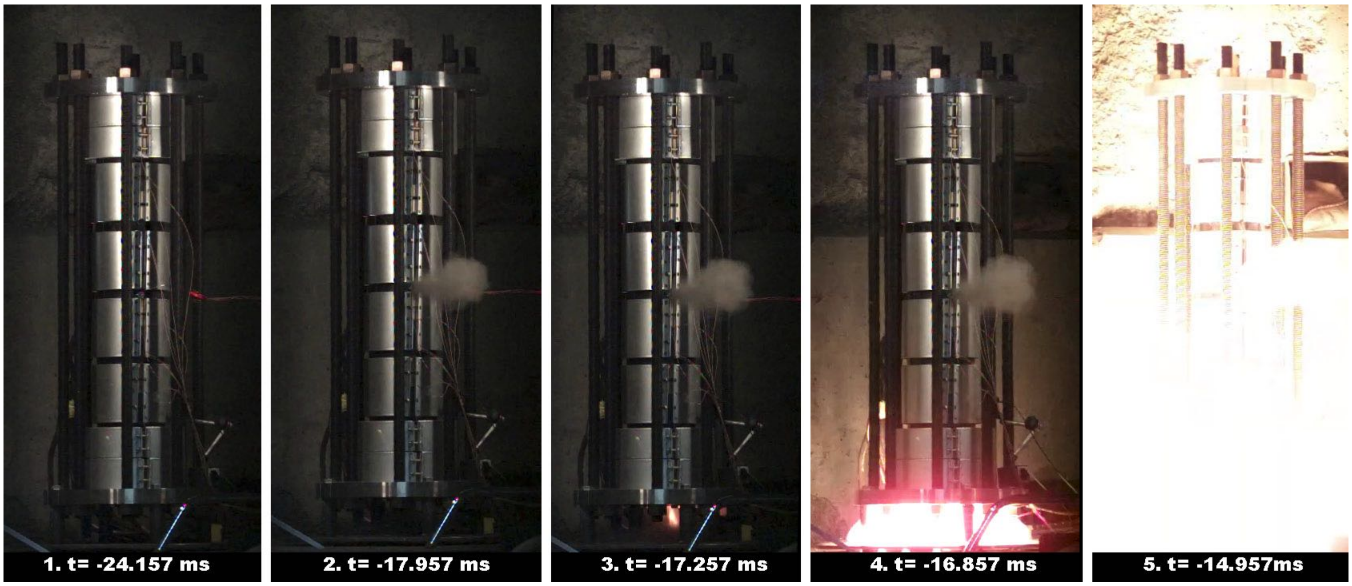


Figure 34. Test 3. Reaction is first visible as ejecta out the central thermocouple port in frame 2. Then in frame 3, flame is visible out bottom glow plug port. In frame 4, flames engulf the lower half of the assembly and the brightness saturates the camera sensor.

7.4. Test 4 Results

The high-speed video for Test 4 revealed qualitative differences in post-ignition behavior compared to the first three tests, probably due to the use of molding prills. Considerable ejecta is observed existing the top vent hole; eventually the ejecta ignites, and a flame front is visible a few inches away from the top plate. The ejecta that has been expelled into the top of the blockhouse then ignites above the shot out of the field of view (as evidenced by a strong illumination source from above). In the final stages of the video, the reaction attains the level of violence observed in Tests 1-3, as the top cap threads are stripped, the top plate dished, and gases are observed to escape from the cap-tube joint to strip off the top heaters.

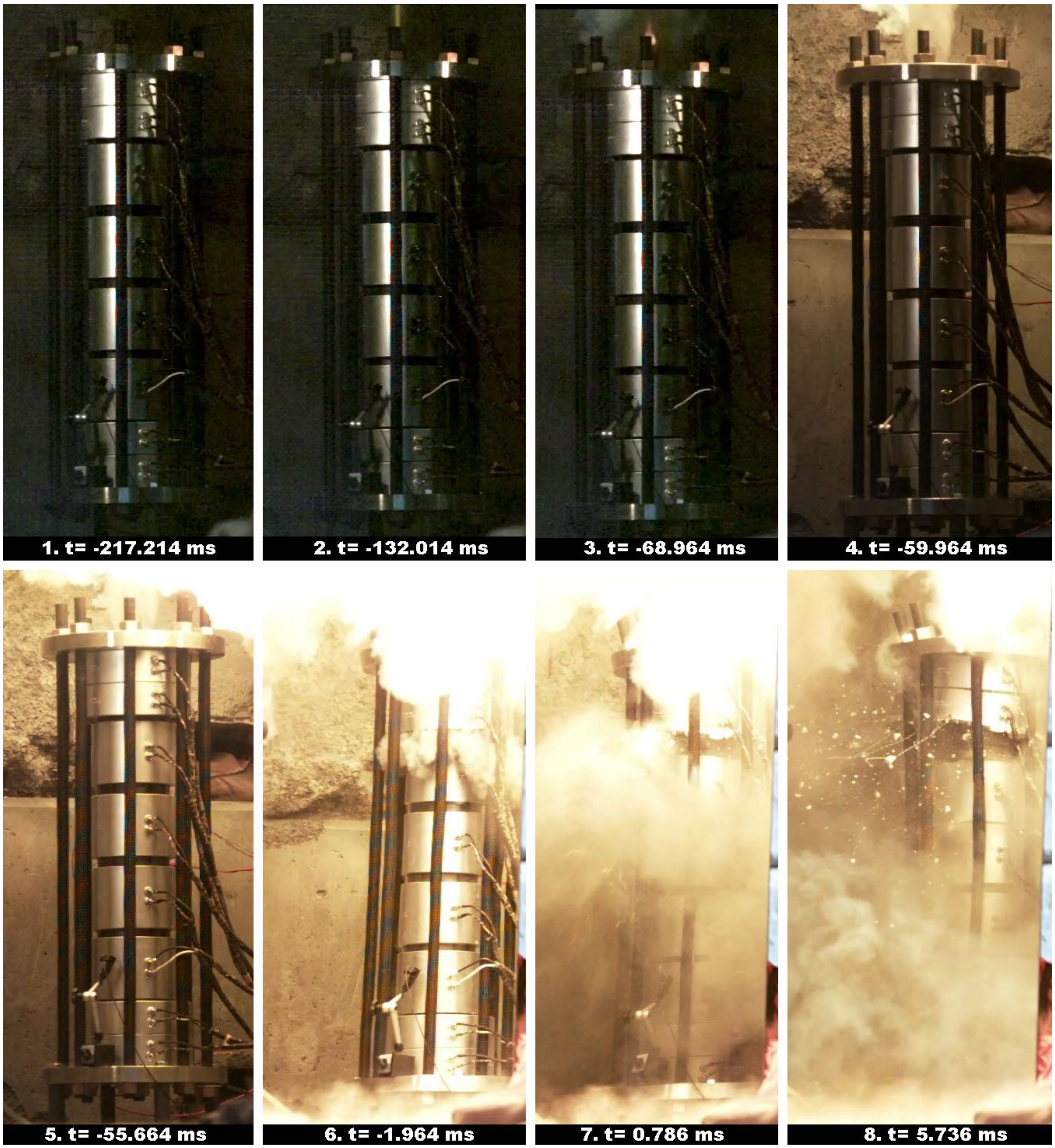


Figure 35. Test 4. Sequence from high-speed video. Frame 1 occurs just before ejecta becomes visible out the top vent hole. In frame 2, the ejecta stream is clear at the top of the frame. In frame 3, the ejecta has developed a flame front, just visible behind the bolt in the foreground of the shot. In frame 4, the ejecta above the shot has ignited and is illuminating the shot from above. In frame 5 this fireball comes into the top of the frame from above. In frame 6 the vessel has failed at the threaded cap-tube joint and ejecta is visible streaming downward from that location. In frame 7 the debris cloud has developed further and the shot is falling over (to the right of the frame). In frame 8 the dished lid, bent all-thread, and damaged heaters are prominent.

7.5. Test 5 Results

The video record for Test 5 is very similar to that of Test 3 (of which this was a repeat). As in Test 3, ejecta is first visible from the top vent port, followed by bright reaction out the bottom, which saturates the sensor.

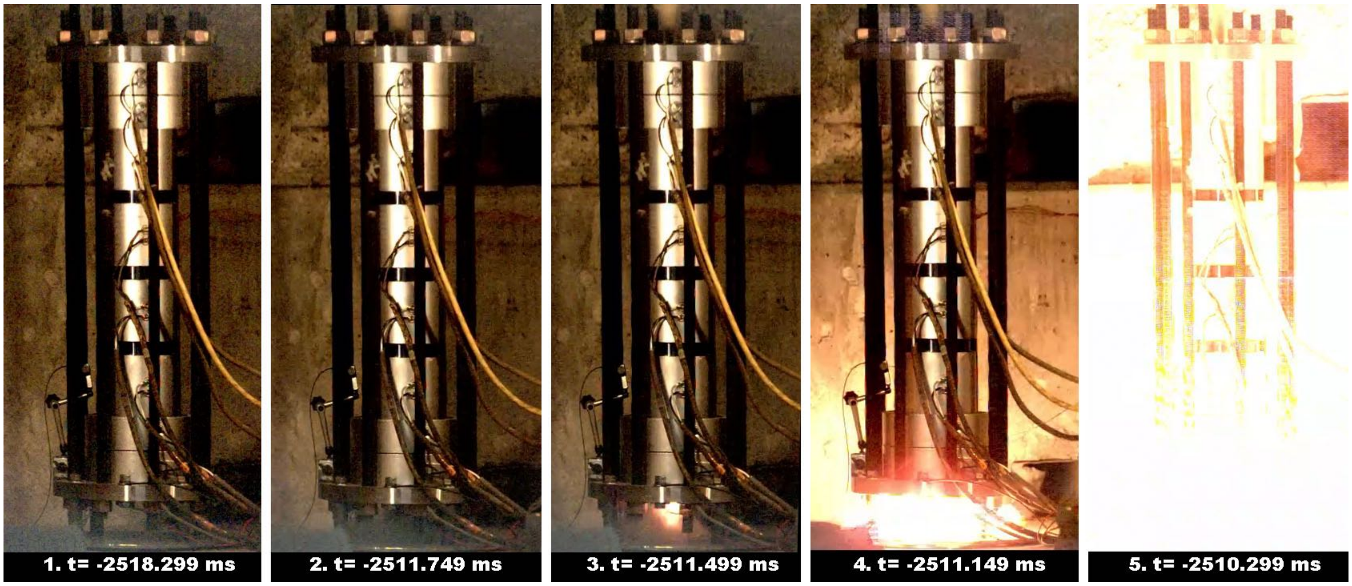


Figure 36. Test 5. Sequence from high-speed video. Frame 1 depicts nominal view prior to reaction. In frame 2, ejecta is visible out top vent hole. In frame 3, ejecta is still being expelled from top vent hole, and ignition is visible out bottom glow-plug holes. In frame 4 the reaction is growing. Frame 5 is the final frame showing an expanding fireball before the sensor is saturated.

Table 5. Post-shot images of Test #5.

Figure 37. View of block-house interior post-shot.

Figure 38. View of damage to heaters (shot has been stood up from the position in which it was found).

Figure 39. Top of shot, as found.

Figure 40. Note deformation of top plate and all-thread.

7.6. Test 6 Results

The video record for Test 6 is very similar to that of Test 4 (of which this was a repeat), further demonstrating repeatability. In the video, the assembly looks like an upside-down rocket motor, as product gas is forced out of the top vent hole, reacting some distance away from the nozzle.

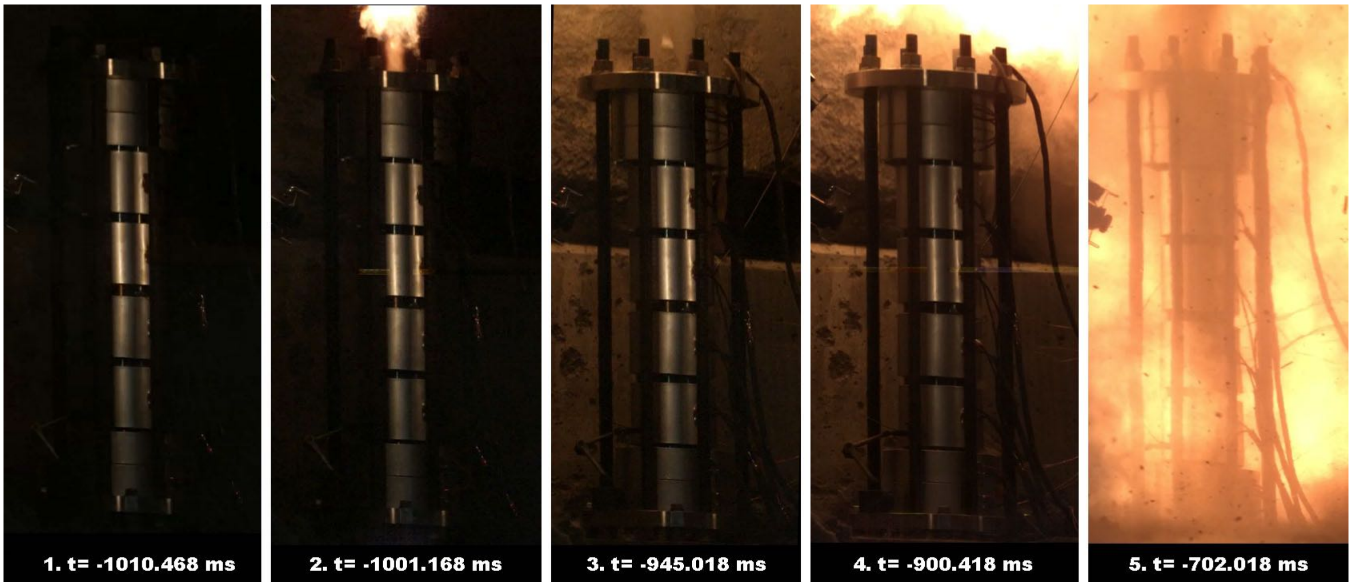


Figure 41. Test 6. Sequence from high-speed video. Frame 1 depicts nominal view prior to reaction. In frame 2, ejecta and flame are visible from top vent hole. In frame 3, ejecta is still being expelled from top vent hole, flame standoff has increased (flame is out of top of frame in ceiling of block house). In frame 4 a fireball is developing above the shot. Frame 5 is the final frame showing an expanding fireball before the sensor is saturated.

Table 6. Images from Test #6

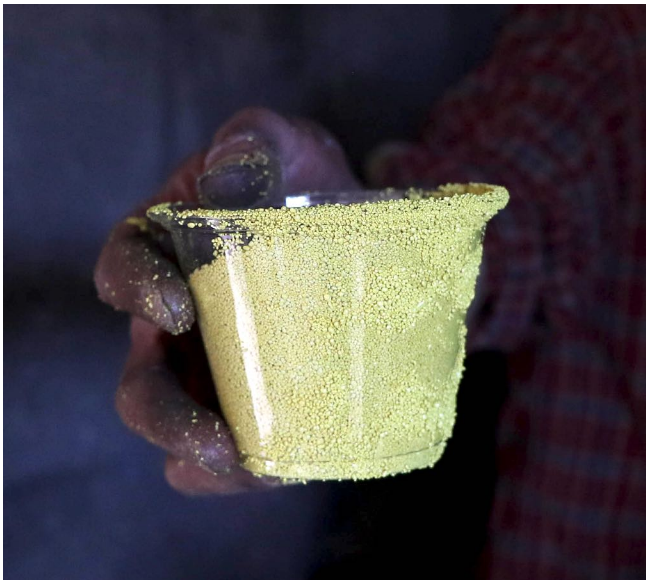


Figure 42. 9502 prills.

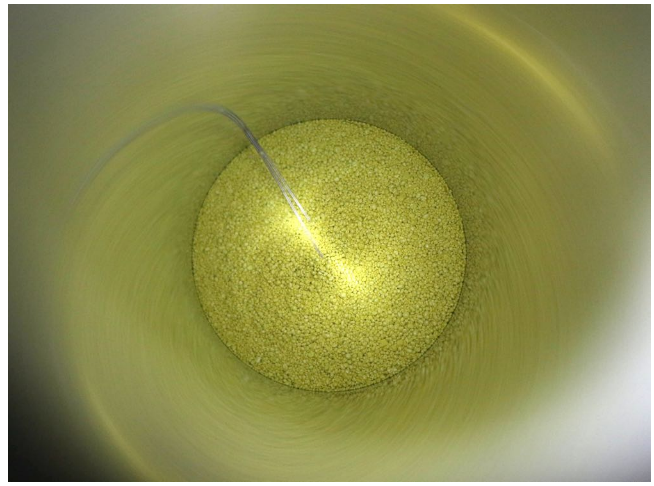


Figure 43. Tube filled halfway with prills, and thermocouples inserted.

Figure 44. View of tube immediately after test was executed.

Figure 45. View of top plate post-test, with burned material evident spread on top plate.

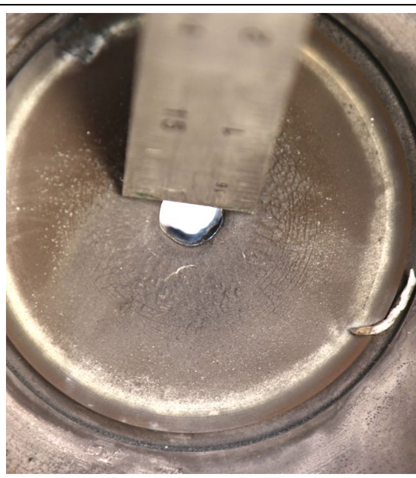


Figure 46. Hole through top cap was enlarged by reaction gases.

Figure 47. Top cap was bowed by internal pressure.

7.7. Test 7 Results

The result of Test 7 is similar to that of Test 6 and Test 4 (of which this was a repeat). For this experiment, a plate was bolted atop the apparatus, to mitigate the upward jetting flame catching fire to the sandbags above the ceiling.

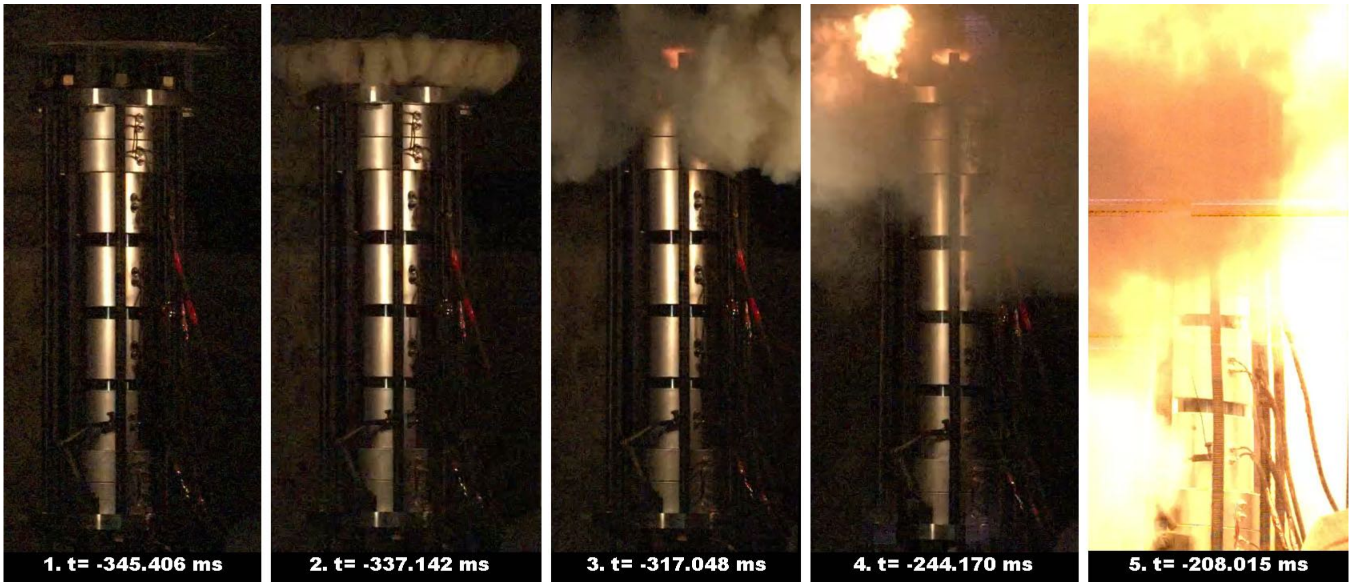


Figure 48. Test 7. Sequence from high-speed video. Frame 1 depicts nominal view prior to reaction. Note a metal plate is bolted a few inches away from the top surface of the shot for this test. In frame 2, ejecta is visible out top vent hole, laterally expanding between the top of the shot and the plate above it. In frame 3, some of the ejecta has ignited a visible flame. In frame 4 the fireball is beginning. Frame 5 is the final frame showing an expanding fireball before the sensor is saturated.

Table 7. Images from Test 7.

Figure 49. A top plate was bolted above the shot on this test to help prevent setting the roof on fire.

Figure 50. Top plate.

Figure 51. Post-test view of top surface of top cap.

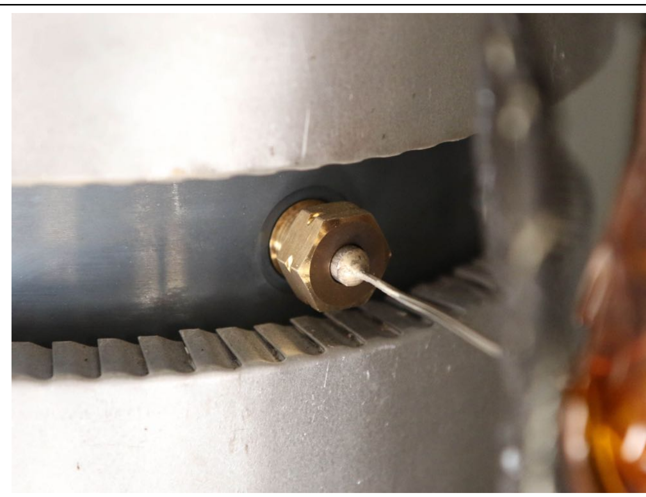


Figure 52. Post-test view of thermocouple fitting.

7.8. Test 8 Results

Test 8 is nominally identical to Test 3 and Test 5. As in Test 5 and Test 3, flame is first visible at the bottom of the shot.

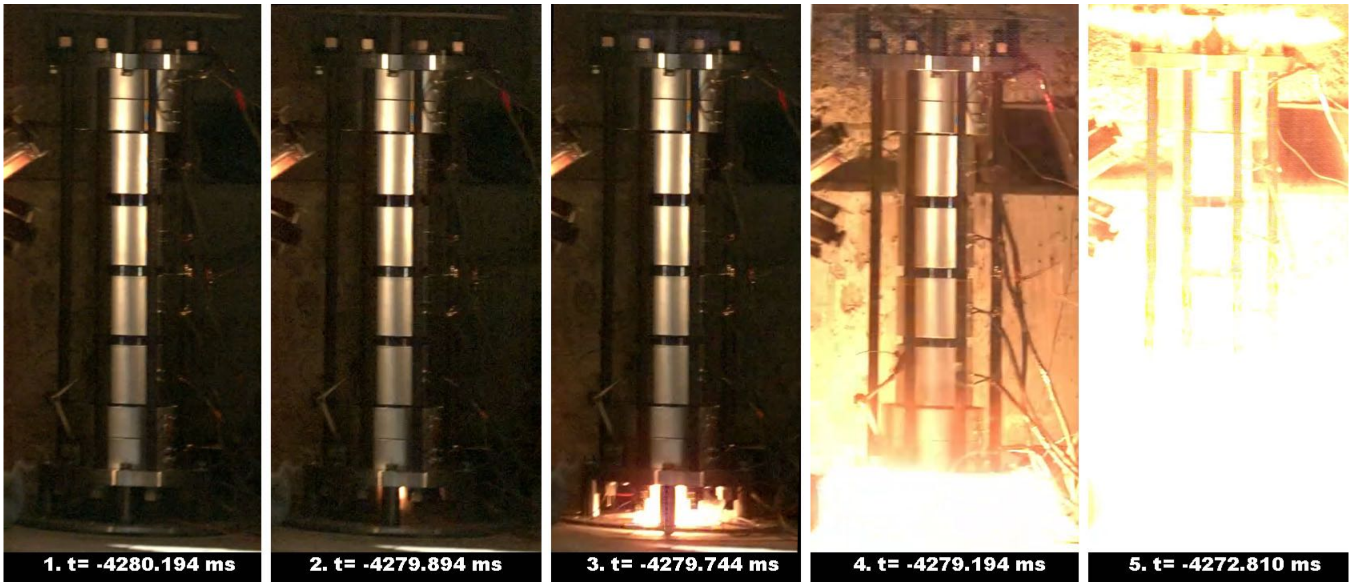


Figure 53. Test 8. Sequence from high-speed video. Frame 1 depicts nominal view prior to reaction. Note a metal plate is bolted a few inches away from the top surface of the shot for this test. In frame 2, flame is visible just starting out bottom vent hole. In frames 3 and 4, the fireball is developing and expanding from the bottom. In frame 5, ejecta from the top vent hole has also ignited.

7.9. Test 9 Results

Tests 9 and 10 utilized a shorter, partial segment of tube to collect baseline data on fragment morphology when detonation occurs. See Figure 54. A 10-inch column of PBX 9502 molding prills was poured into the tube, atop the standard thermite ignition system. A 3-inch x 3-inch column of C-4 was inserted atop the prills. An RP-83 detonator was embedded into the C-4 and detonated.

No video was captured for Test 9.

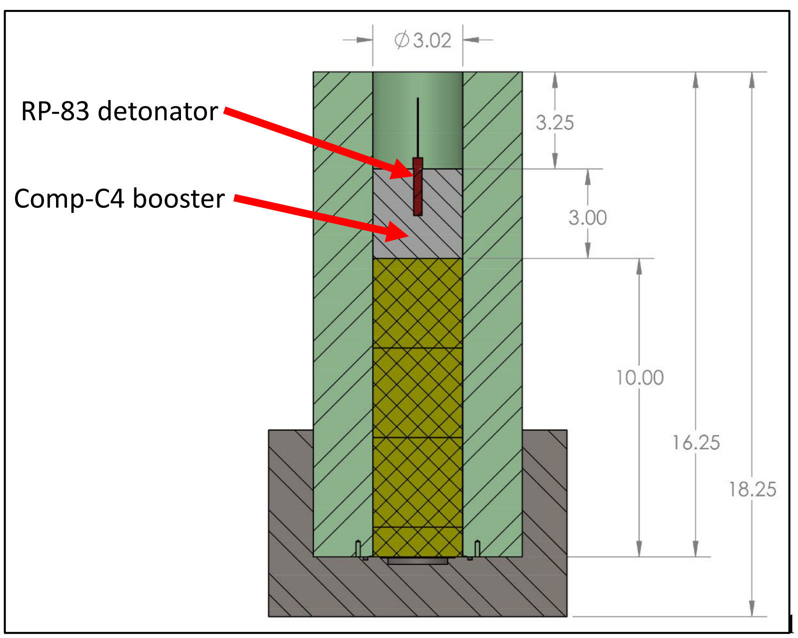


Figure 54. Shortened tube apparatus for deliberate detonation baseline. For Test 9, pour-density prills were used. For Test 10, consolidated pellets were used.

7.10. Test 10 Results

Test 10 was identical to Test 9, but using consolidated pellets instead of prills (Figure 54). No video was captured for Test 10.

Figure 55. Test 9, deliberate detonation of prills. View of outside surfaces of fragments.

Figure 56. Test 9, deliberate detonation of prills. View of inside surfaces of fragments.

Figure 57. Test 10, deliberate detonation of consolidated pellets. Left side shows inside surfaces of fragments, right side shows outside surface of cap.

Figure 58. Test 10, deliberate detonation of consolidated pellets. Left side shows outside surfaces of fragments, right side shows inside surface of cap.

8. Temperature Plots

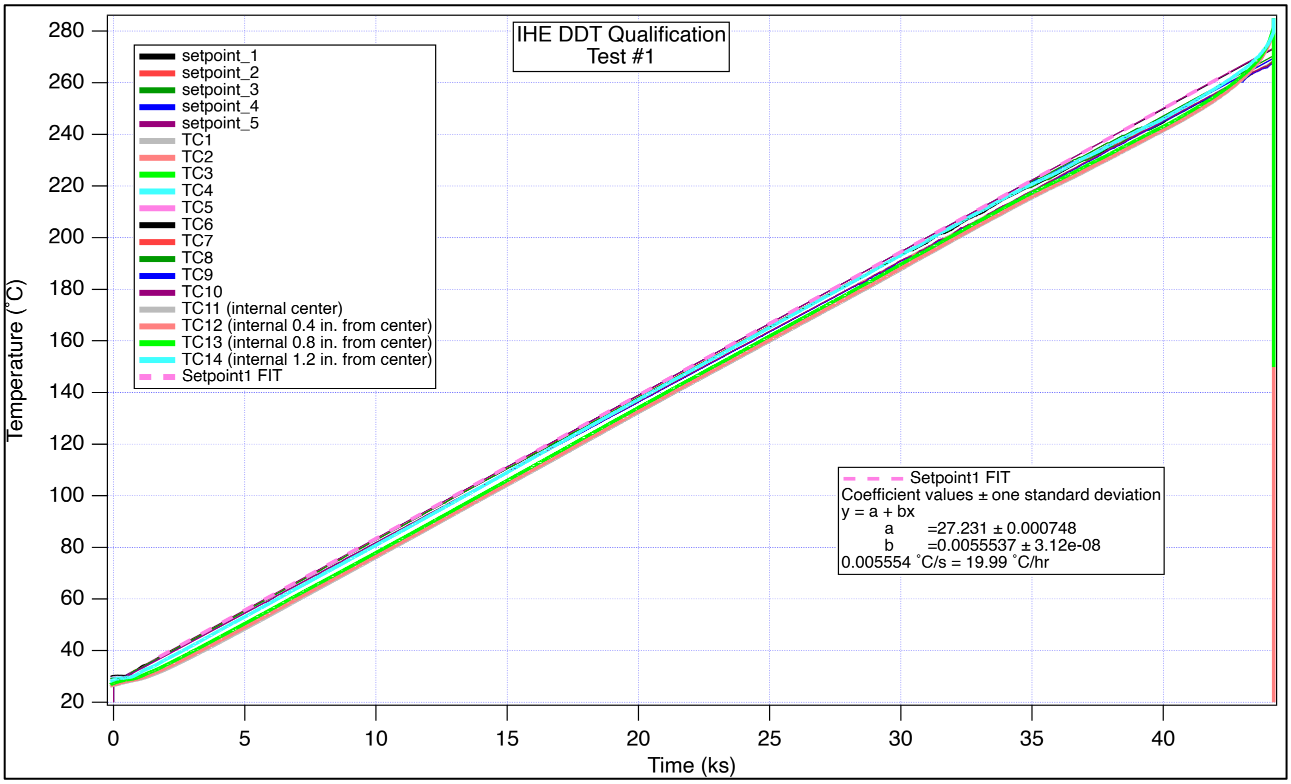


Figure 59. Test 1, all temperature data. Refer to Figure 9 for thermocouple locations.

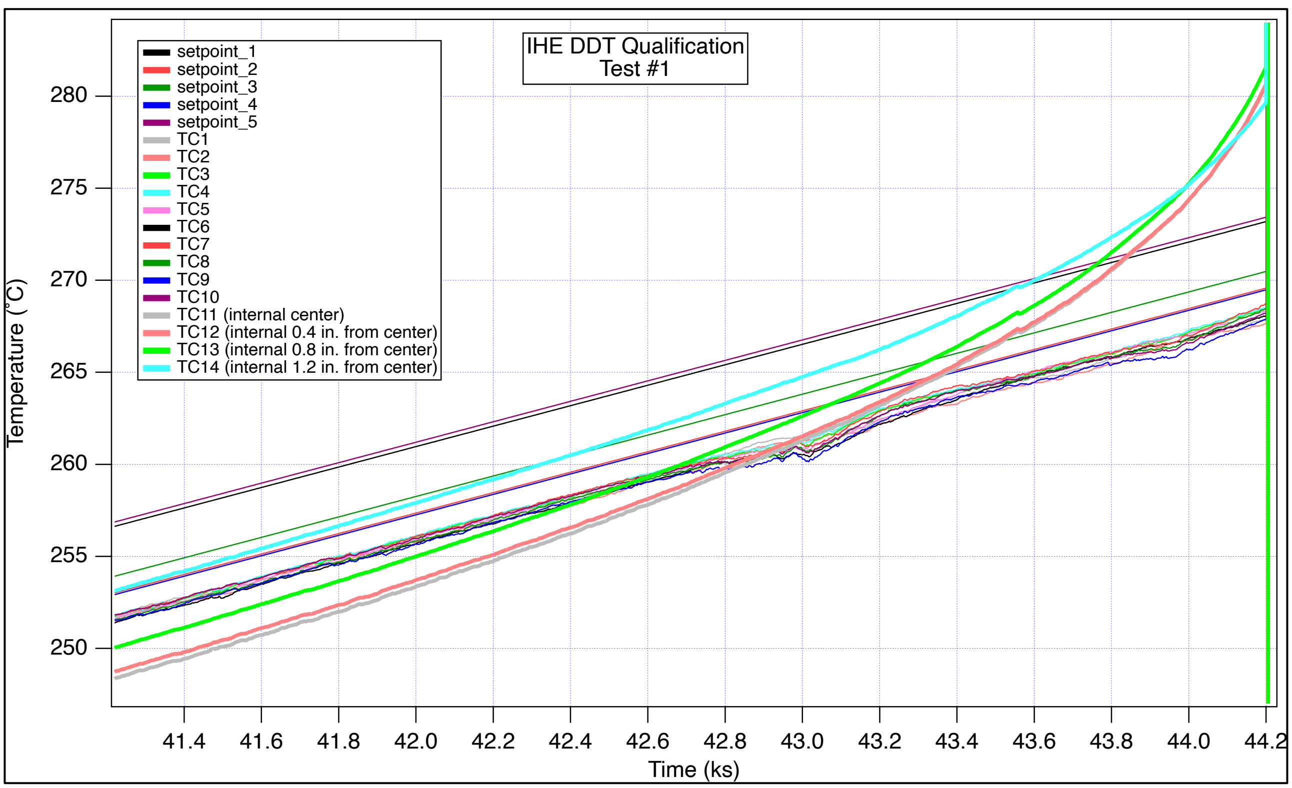


Figure 60. Test 1, detail view of cookoff. Refer to Figure 9 for thermocouple locations.

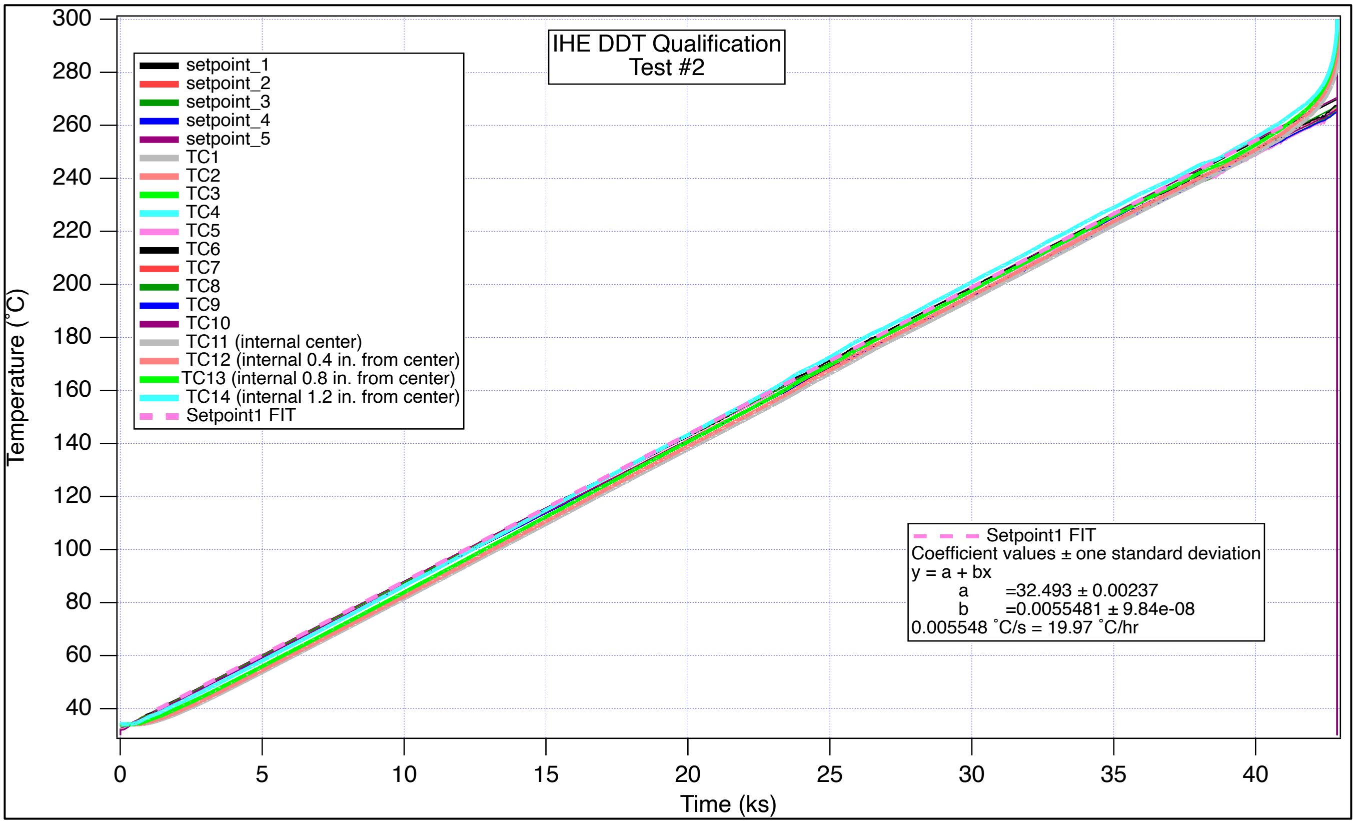


Figure 61. Test 2, all temperature data.

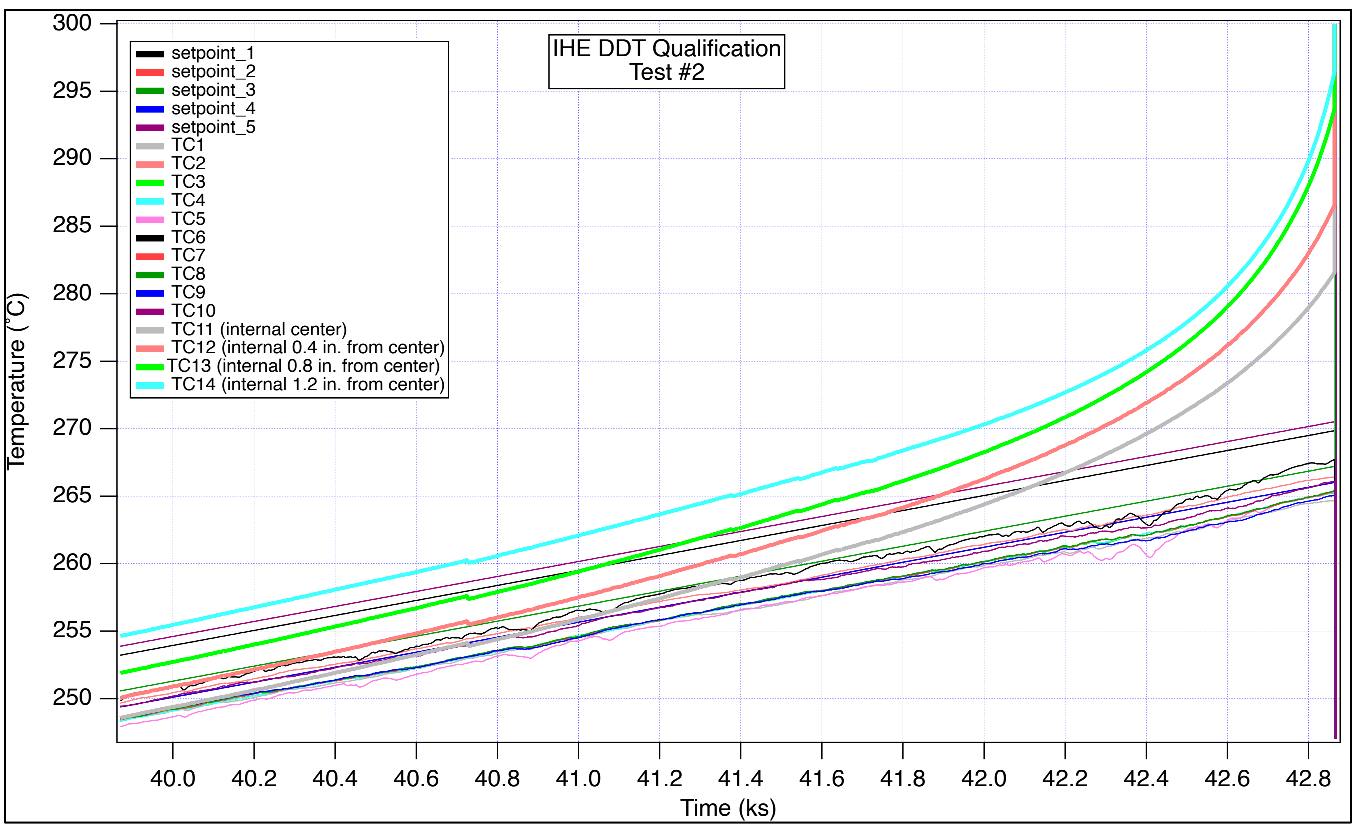


Figure 62. Test 2, detail of thermal runaway.

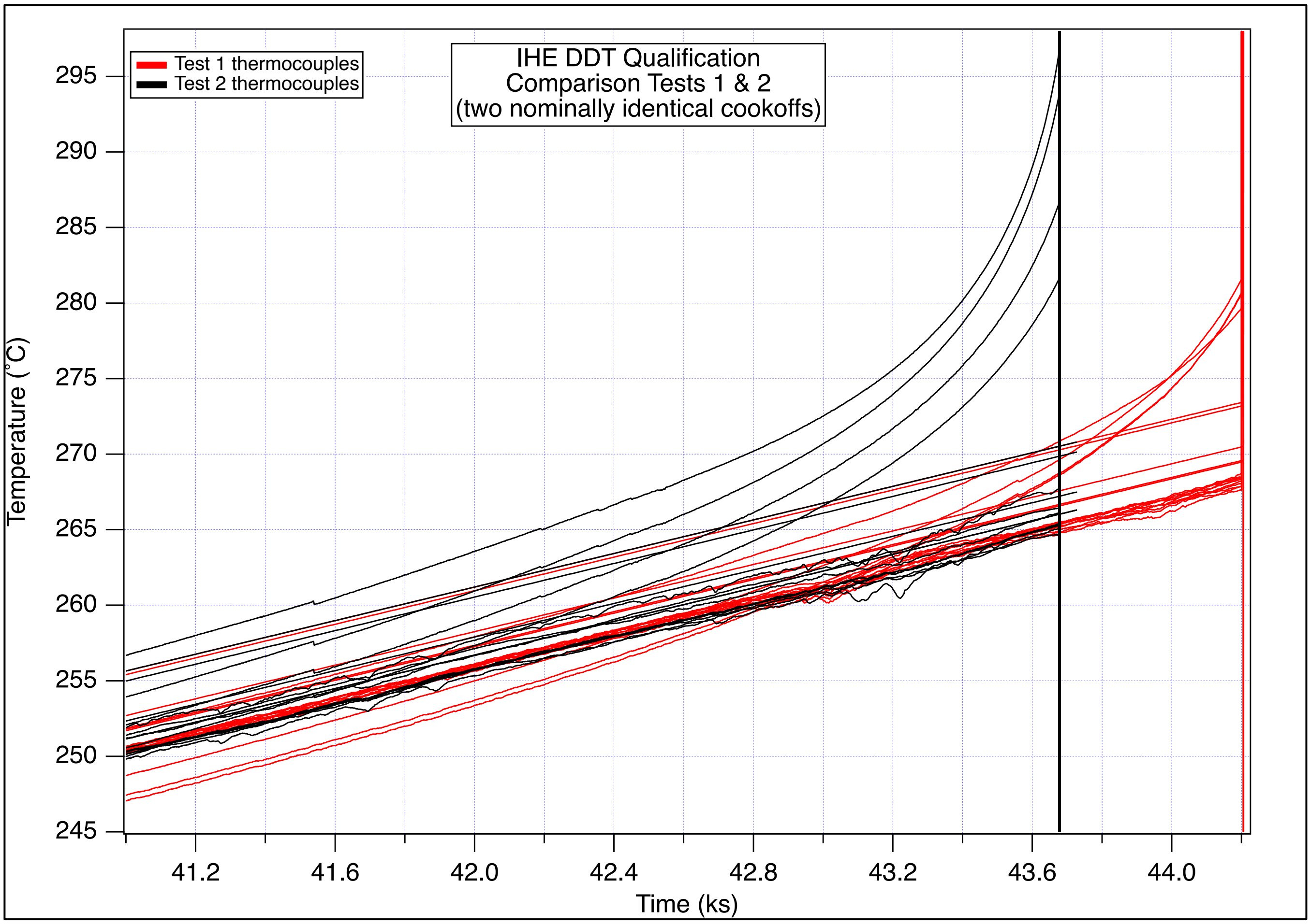


Figure 63. Comparison between Tests 1 and 2. The time on Test 2 has been shifted so that the time was synchronized at a temperature of 32.4˚.

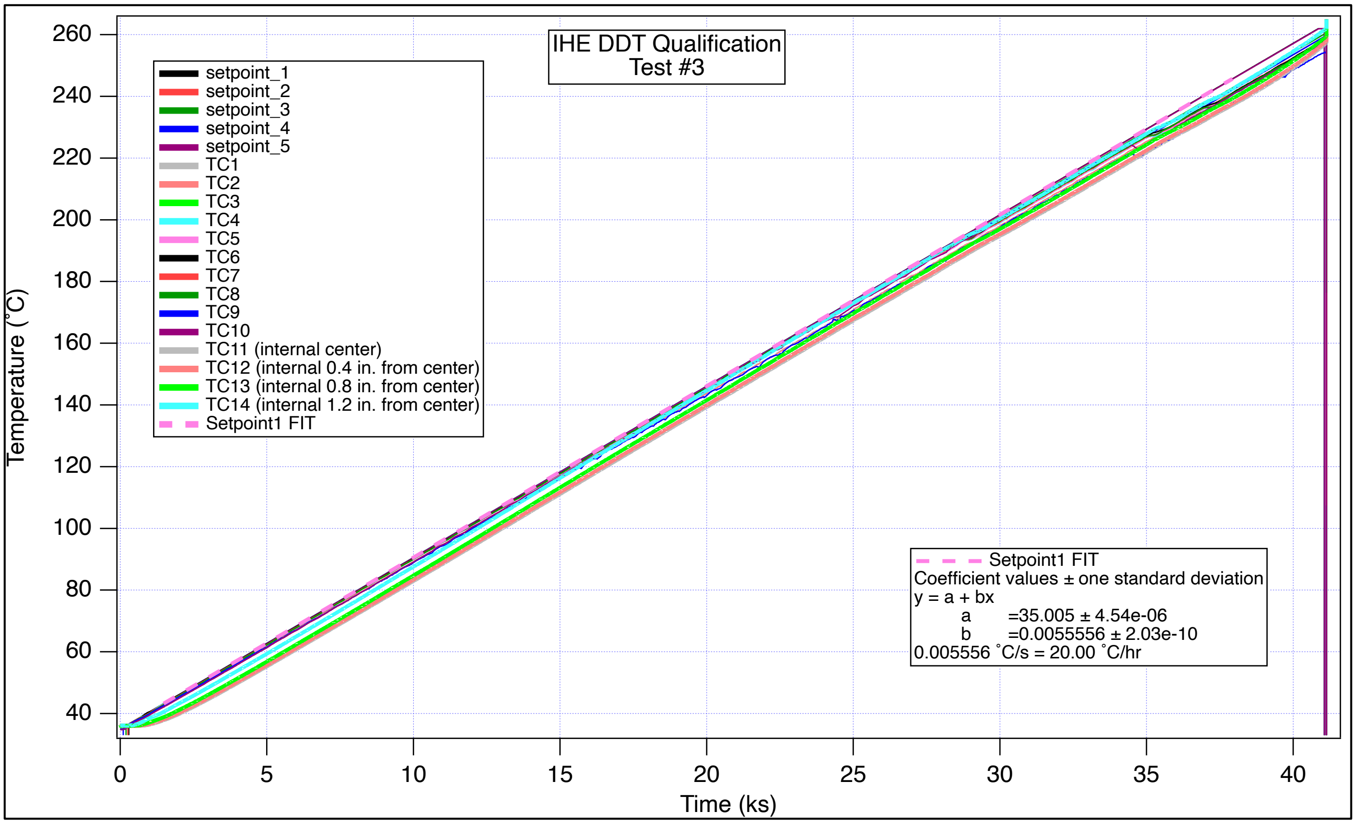


Figure 64. Test 3, full temperature records.

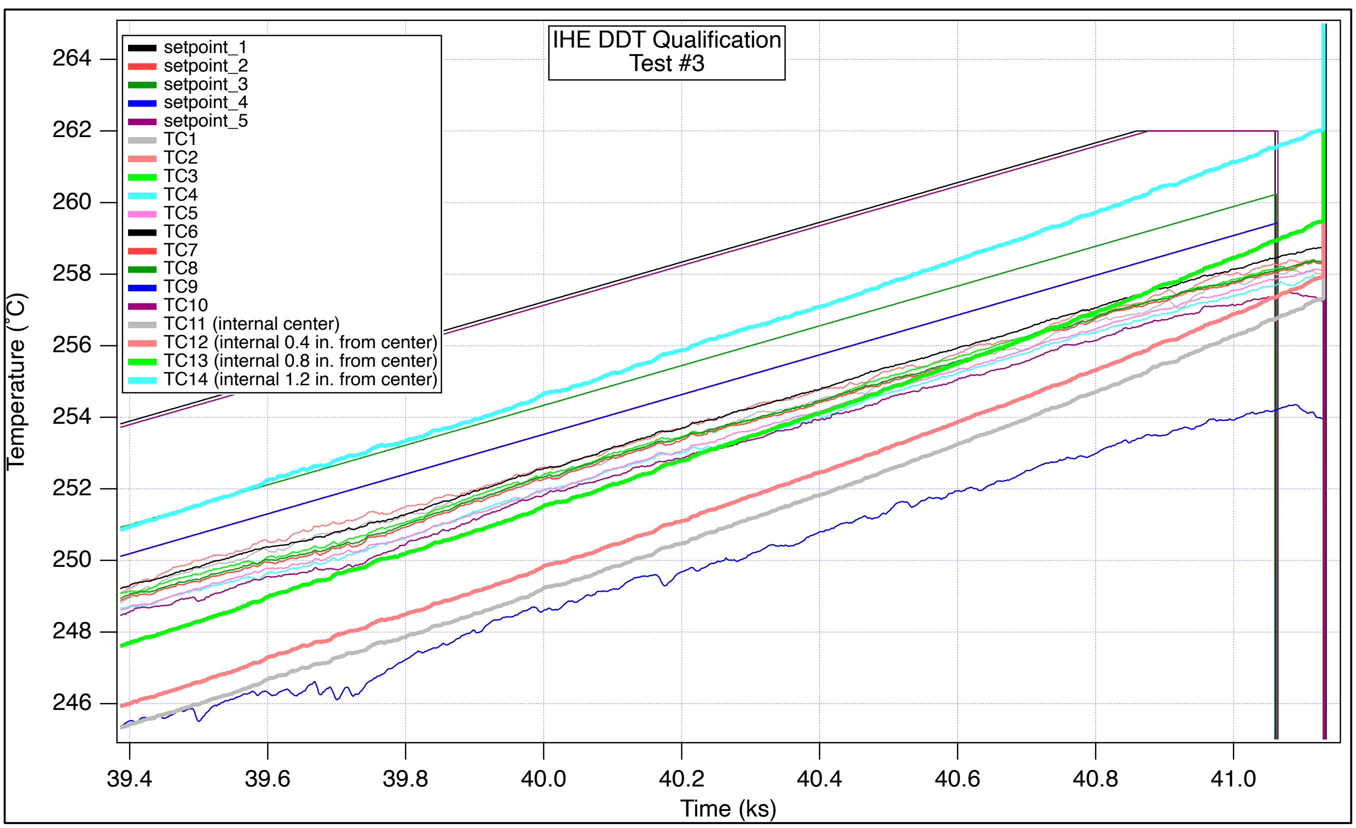


Figure 65. Test 3, detail illustrating temperature gradient at time of deliberate ignition.

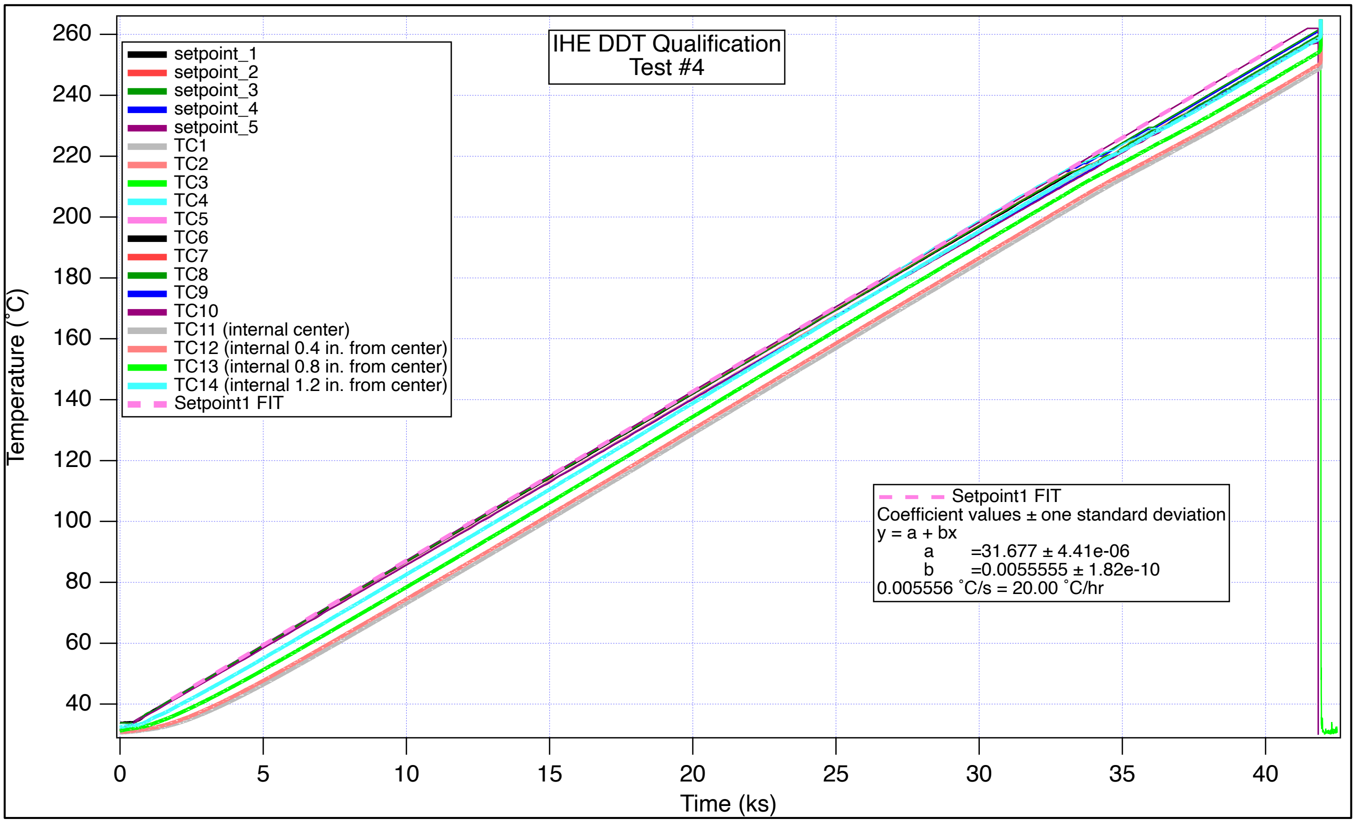


Figure 66. Test 4. Entire thermocouple record.

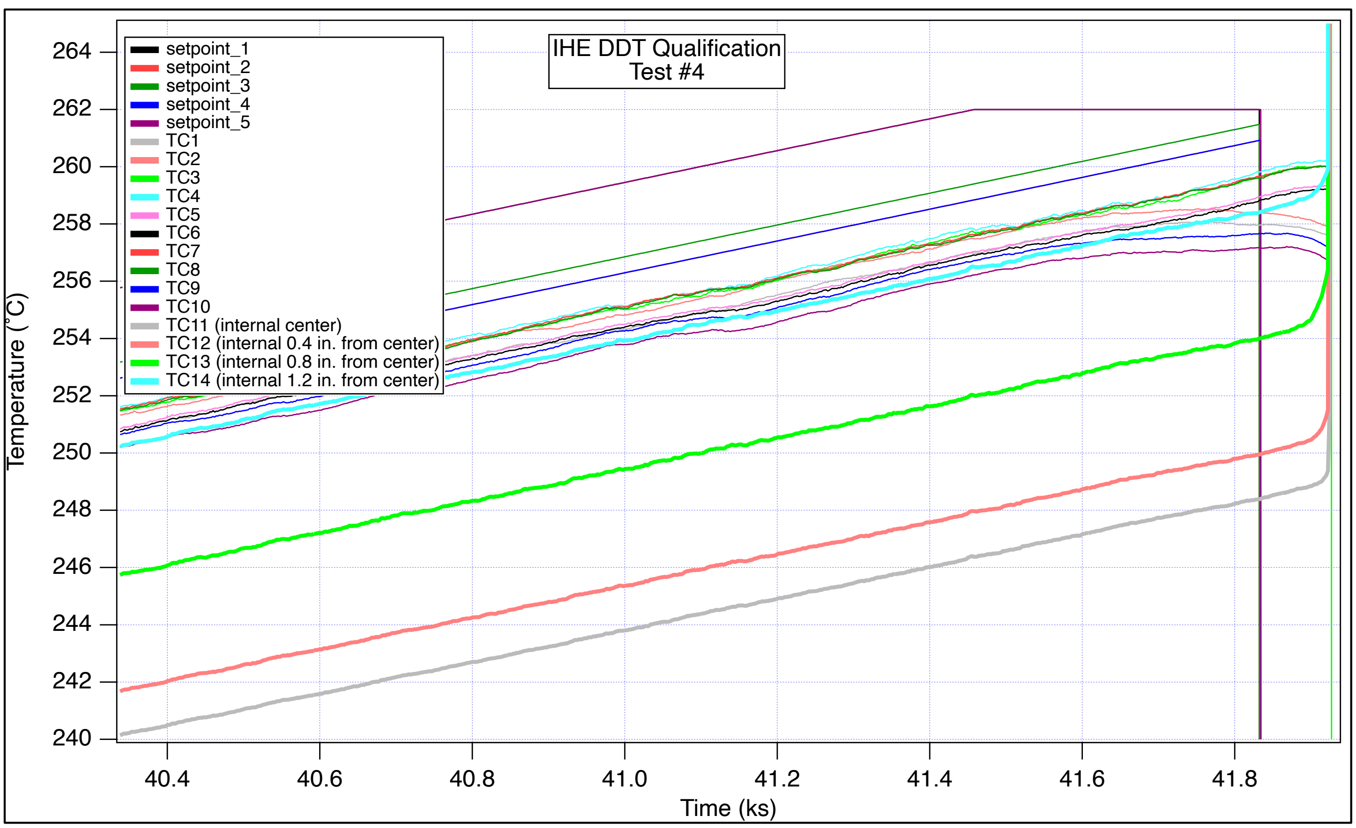


Figure 67. Test 4, detail view at ignition, showing temperature gradient.

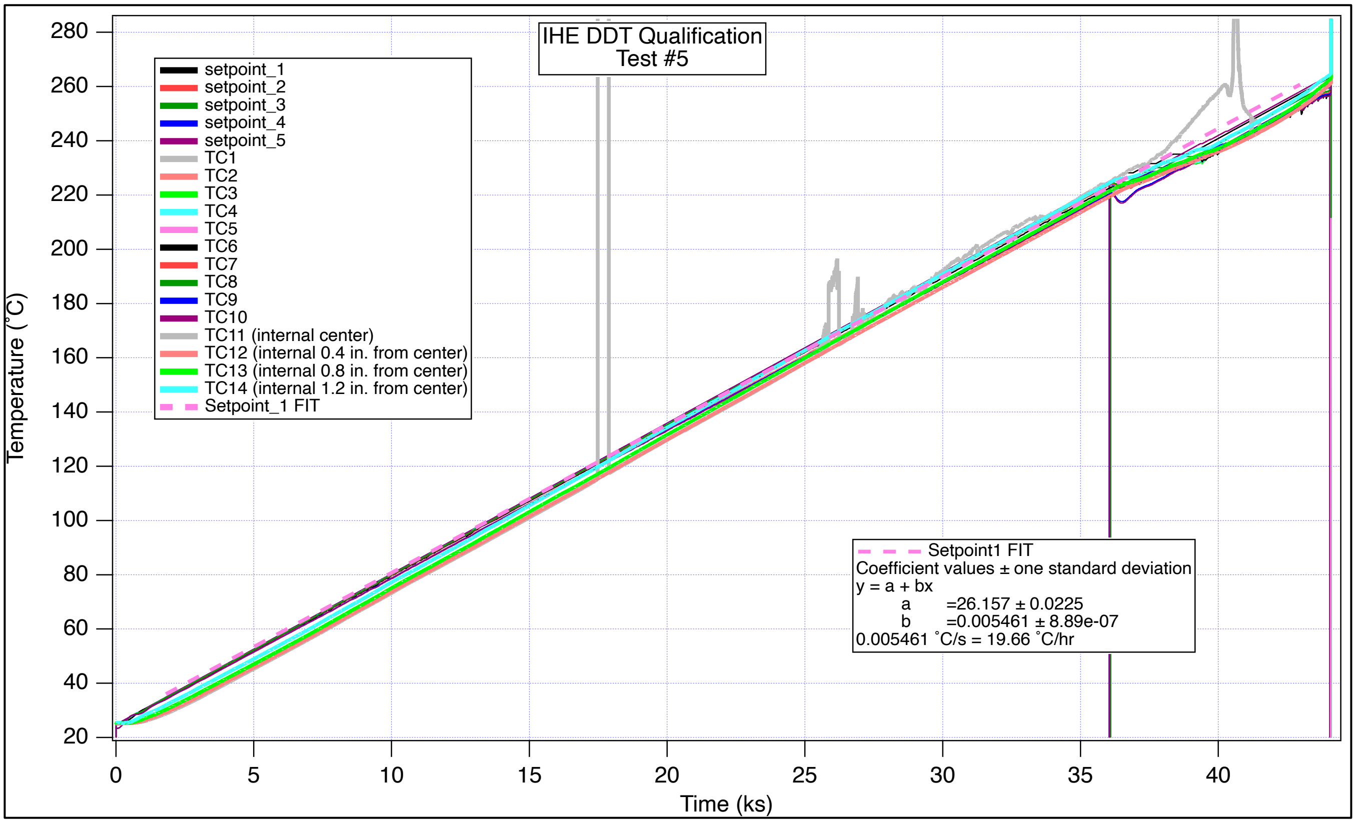


Figure 68. Test 5 thermocouple data, entire duration. Excursions by TC11 are indicative of TC failure. Setpoints deviate briefly at ~36 ks when heaters were accidentally, briefly turned off.

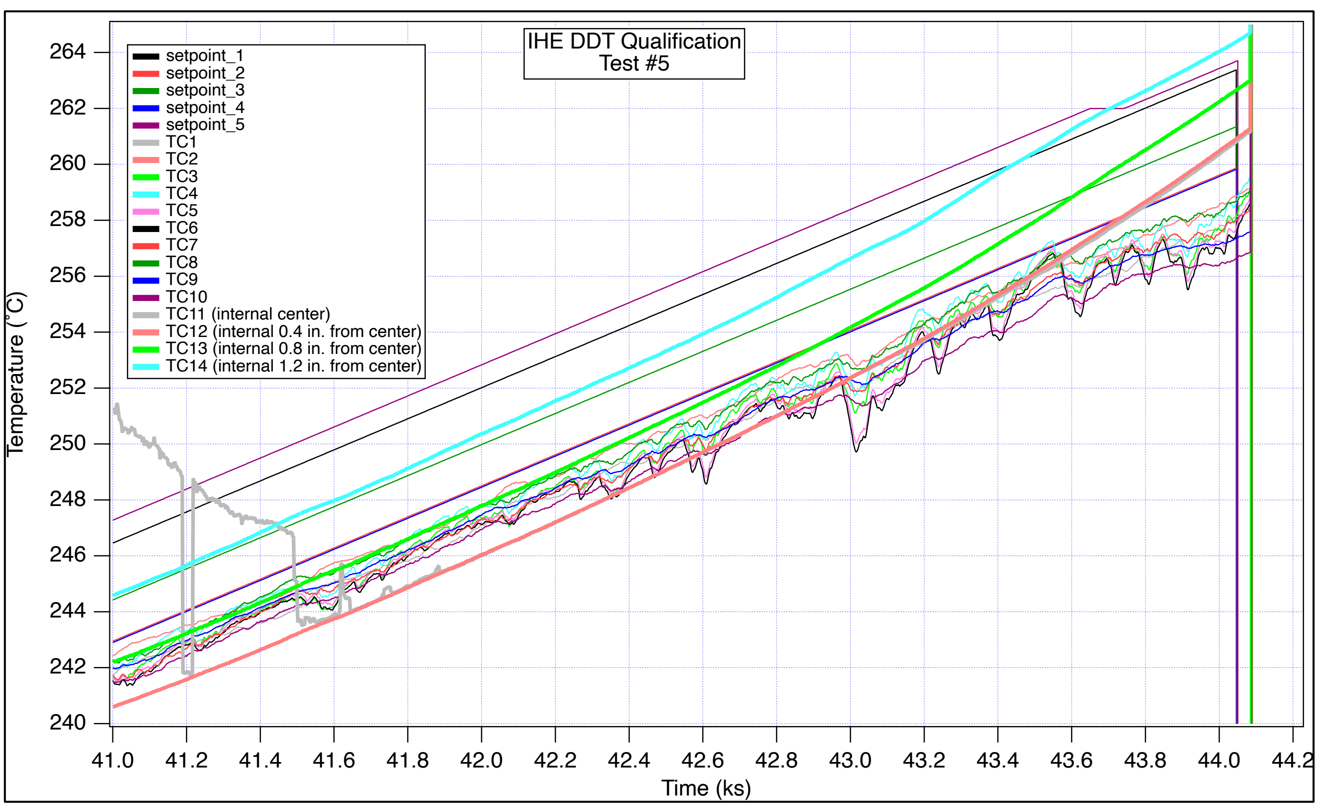


Figure 69. Test 5, thermocouple data, detail at ignition.

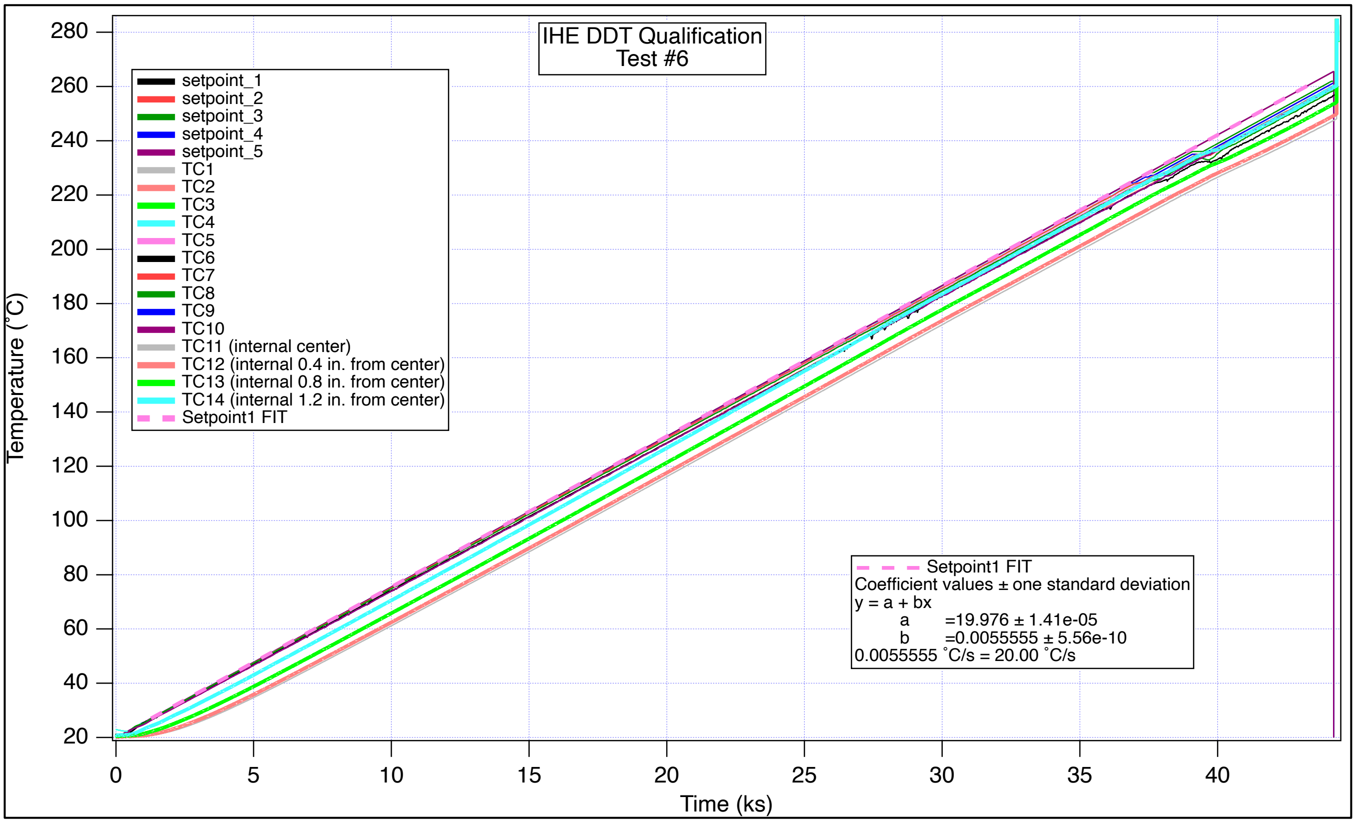


Figure 70. Test 6 thermocouple data, entire duration.

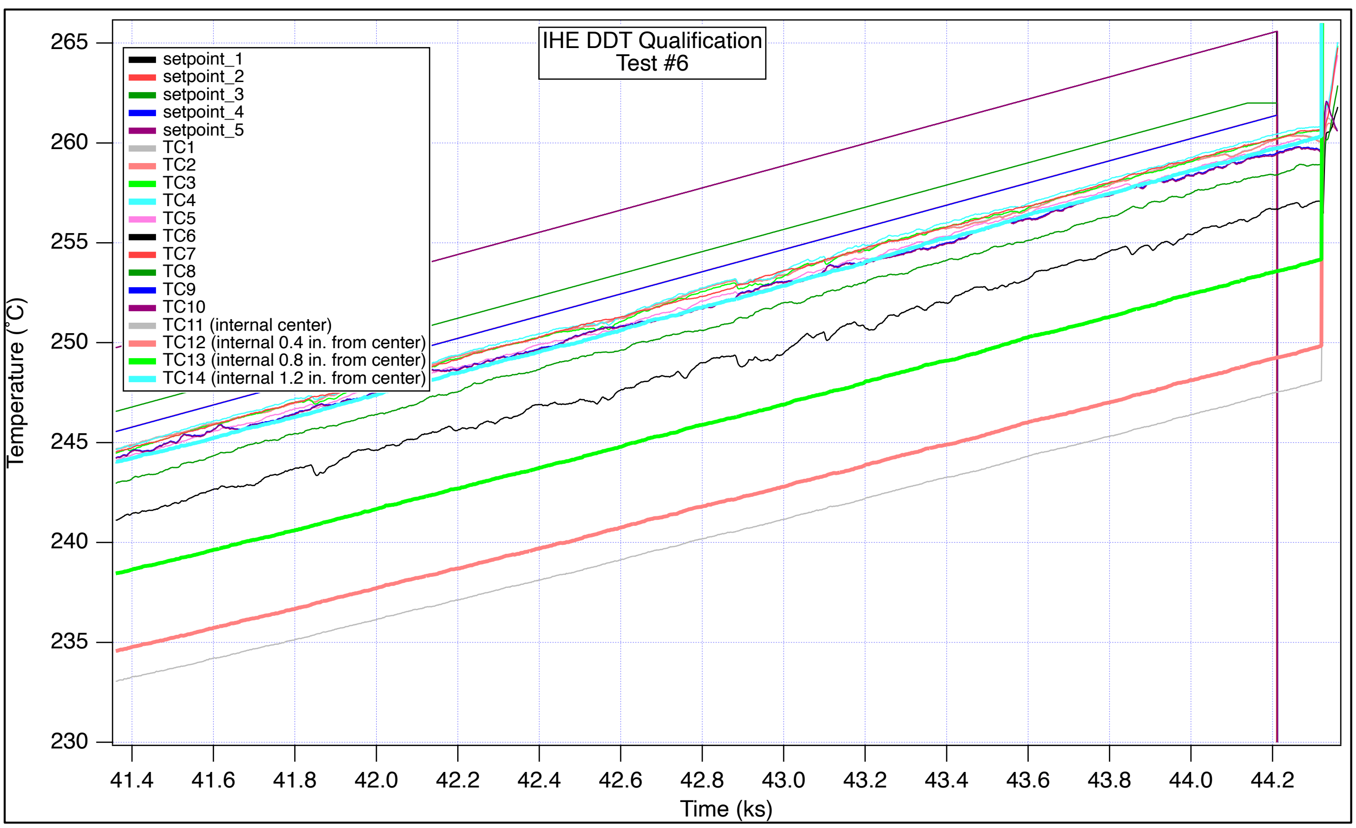


Figure 71. Test 6, thermocouple data, detail at ignition.

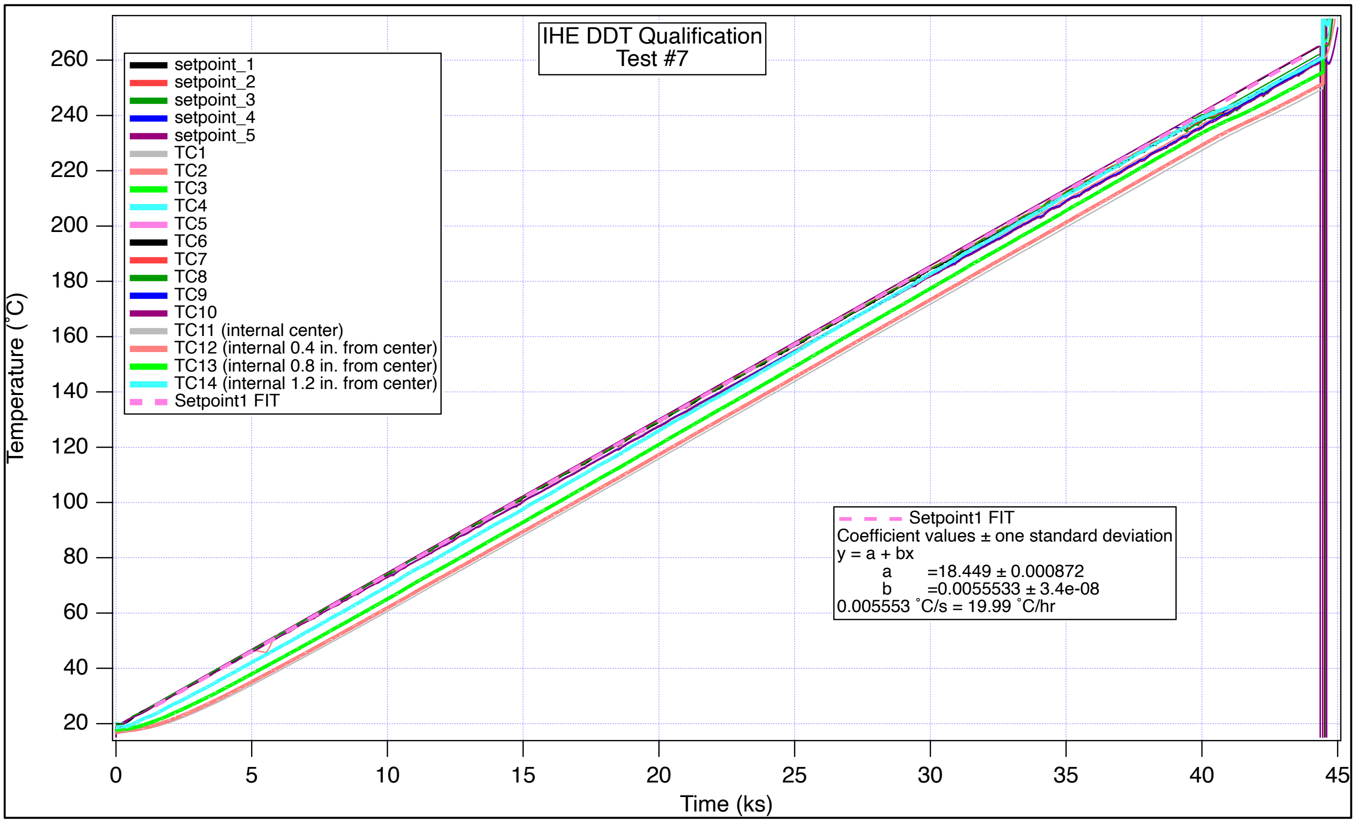


Figure 72. Test 7 thermocouple data, entire duration.

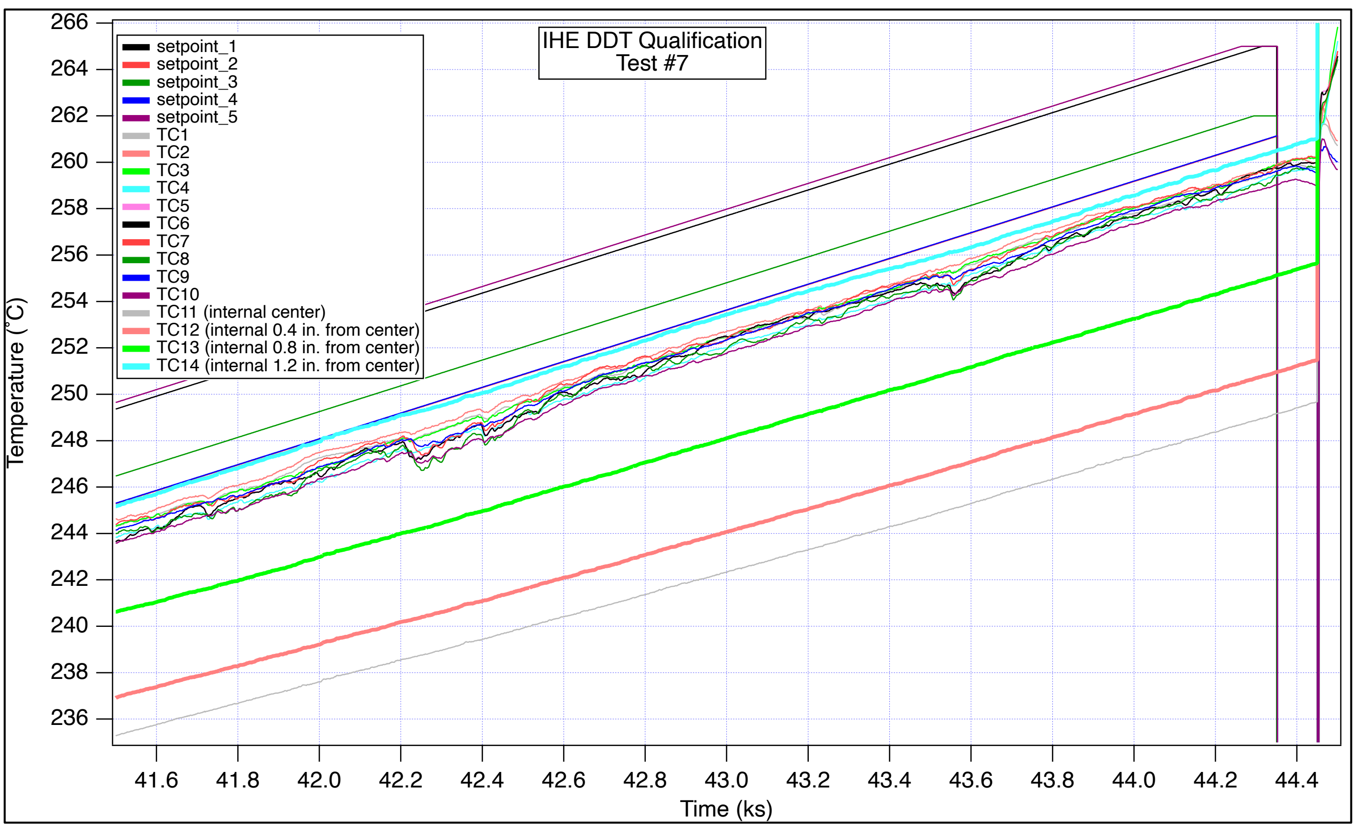


Figure 73. Test 7, thermocouple data, detail at ignition.

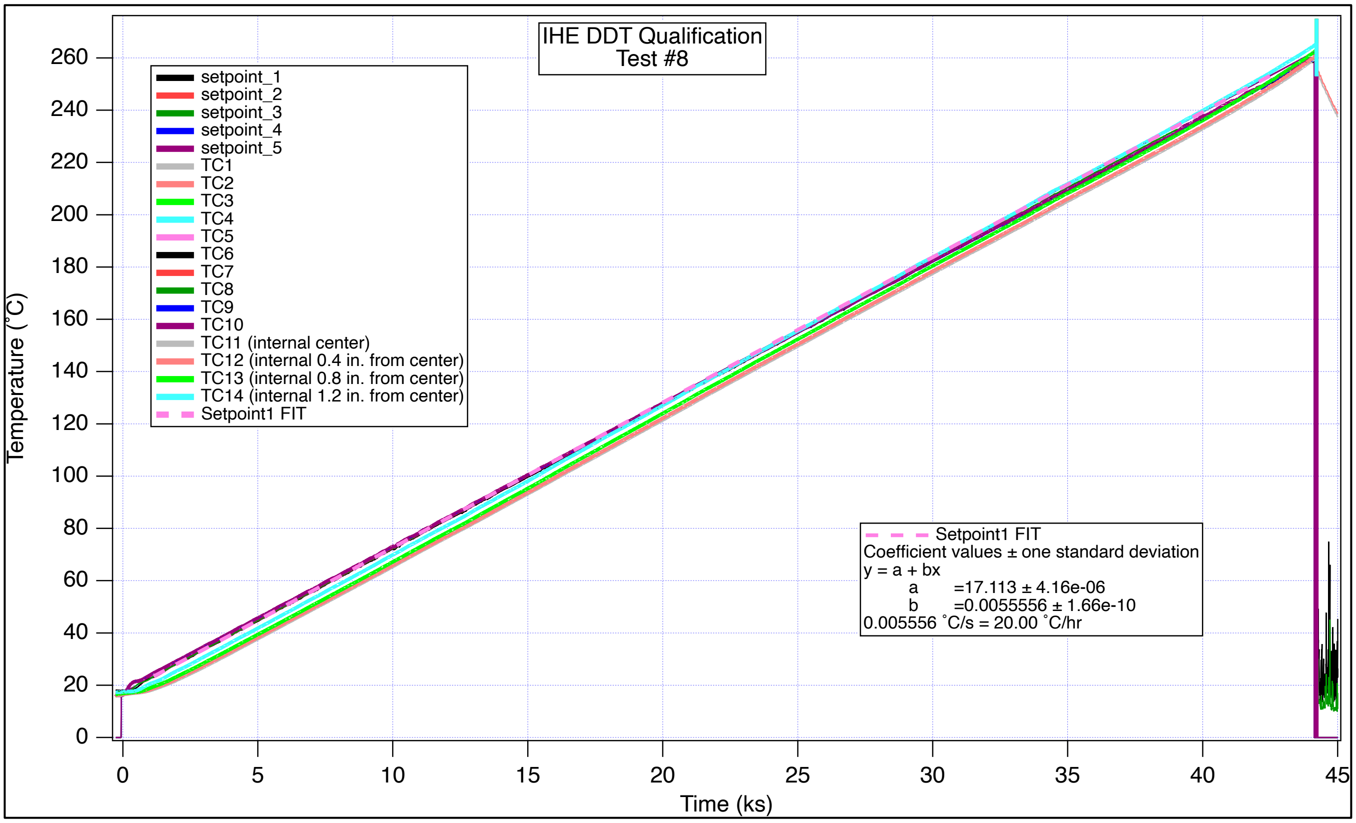


Figure 74. Test 8 thermocouple data, entire duration.

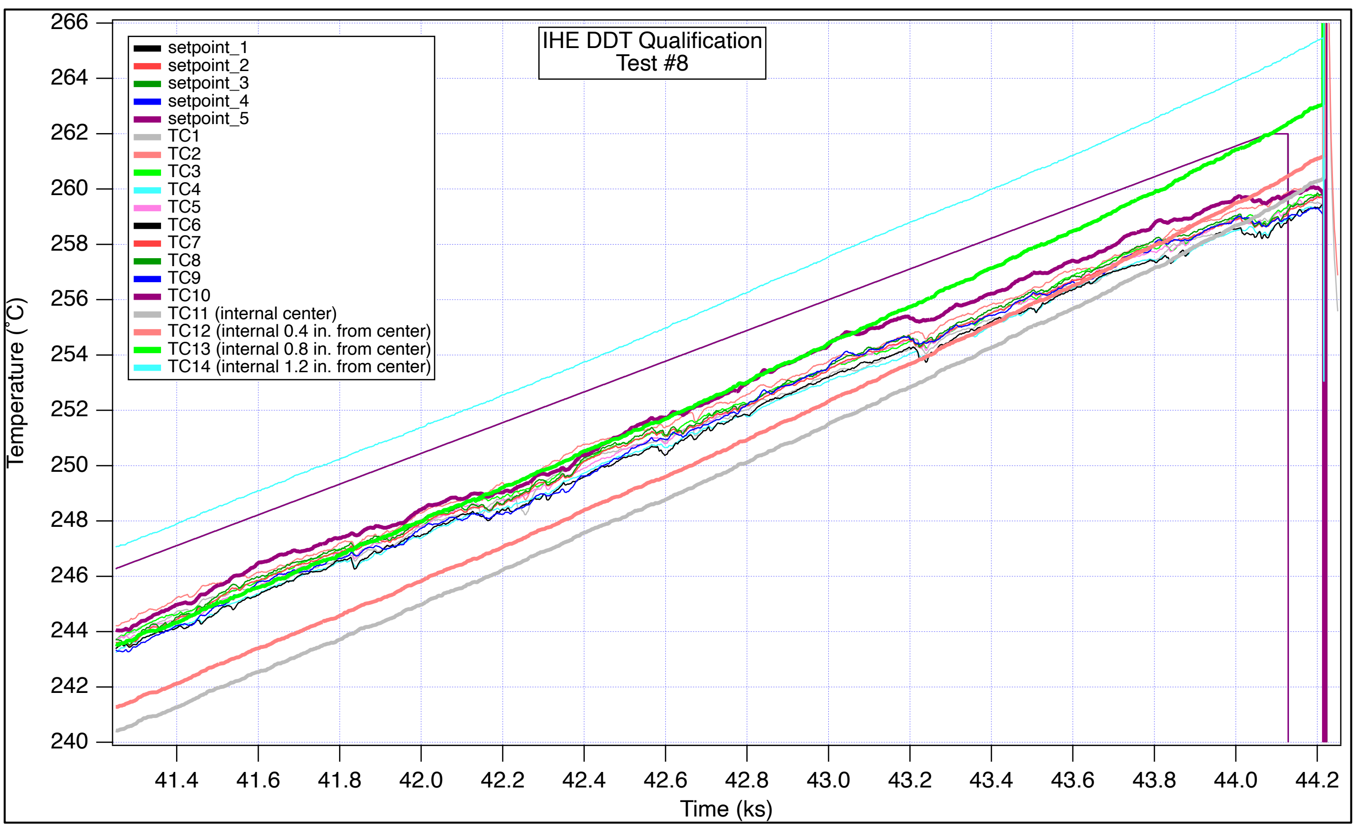


Figure 75. Test 8, thermocouple data, detail at ignition.

9. Conclusions

A new Insensitive High Explosive (IHE) qualification standard exists. The detonation-to-deflagration (DDT) portion of the standard outlines a test series using heavy steel cylinders. The cylinder is filled with the explosive and then heated until self-ignition, or else heated and then deliberately ignited. An experiment to meet the standard was designed and fabricated, including the remotely controlled heating and ignition system. A detailed procedure was established for experiment assembly and execution. A series of ten experiments was performed with PBX 9502. All aspects of the design functioned as intended. High-speed video, temperature, and PDV data (for one experiment) were collected. All experiments exhibited similar explosive response, consisting of a relatively benign pressure burst. The observed violence was far below that of a detonation. Additionally, two shortened sections of tube were deliberately detonated to collect baseline fragment morphology.

Some lessons were learned and minor design improvement identified that might benefit future attempts to execute these tests:

1. The baseplate should be round. The square baseplate prevents proper use of the assembly stand. Moreover, having the shot on a round baseplate permits manual adjustment of position inside the blockhouse, and makes it easier to remove the shot from the blockhouse after the test.
2. If internal thermocouples are to be fielded as we did (it is not required per the qualification standard), the dimensions of the pellets may be an issue. The thermocouples must align precisely with the interface of a pellet, at the midplane of the tube. In our case, every pellet was within machining tolerance, but all pellets were systematically oversized (rather than averaging to the nominal dimension). The error in height was additive, such that the interface location was not aligned with the thermocouples. One pellet had to be trimmed in order to achieve the required alignment.
3. For safety purposes, an experiment that has self-disassembled can be approached and components post-processed. However, when the assembly remains partially intact (as it did in these experiments), we perform a “kill-cook” on the assembly before disassembling it. The kill-cook is a process to render the assembly safe by heating until all IHE residues are chemically decomposed to harmless products. After the experiment deflagrates, we leave the firing site locked out overnight, to allow all components to cool below the exclusion temperature at which approach is permissible. Then personnel approach to fix or replace the external heaters as necessary. Then the firing site is again placed into a firing state, and the heaters are once again remotely controlled to achieve a high temperature, well in excess of the critical temperature (e.g. 400 ˚C) for a suitable duration. This ensures that all energetic has been consumed. After this kill-cook everything is allowed to cool overnight a second time, still with the firing site locked down, before we approach and perform the disassembly.
4. We expected that the PBX 9502 would react violently enough to break the assembly apart, leaving hunks of metal that could be individually removed from the blockhouse. Instead, the entire assembly remained intact (unsealed, but still bolted together). This necessitated use of a portable band-saw to cut the all-thread to permit disassembly. This was an acceptable solution that I would not hesitate to use again. In the planning stages, consideration should be given to how the extremely heavy shot will be removed from the blockhouse after the experiment. Using a round baseplate as recommended above allows the inert apparatus to be placed on its side and rolled.
5. While a high-speed video camera is not required in the qualification standard, it provides the only record of when and how the vessel bursts. We considered the high-speed video and the surveillance cameras inside the blockhouse to be crucial for properly assessing hazards that might be encountered in the blockhouse after the test was completed.
6. Fielding PDV on the first test proved unnecessary and was discontinued, because the test results were so obviously sub-detonative. Also, the qualification standard allows for the use of deliberate detonation baseline experiments instead of PDV, should it become necessary.
7. The experiment—with PBX 9502—was prone to behave like an upside-down rocket engine, and as such can readily set fire to flammables in the immediate vicinity. In fact, this experiment was more likely to start a fire than with a “standard,” deliberately detonated shot—albeit limited to middle of the firing site. The fragment mitigation surrounding the shot is intended to capture any primary fragments that might be produced by detonation (despite the improbability of DDT occurring). Ironically, the mitigation to prevent fires caused by hot fragments escaping the mound makes fires confined to the mound more likely. In one instance we caught fire to the plywood flooring; another time we caught fire to the canvas of the sandbags of the roof. Fires within the boundaries of the firing site are anticipated outcomes (fragment mitigation serves to prevent fires in brush outside the firing mound boundary). However, it is still wise to minimize the flammable material incorporated into the fragment mitigation structure so that any resulting fires stay as small as possible.

Unsurprisingly, PBX 9502 qualifies as an IHE according to the new standard. The experiment design and details provided in this report should prove valuable for other organizations that hope to qualify an explosive as an IHE.

10. Acknowledgments

We gratefully acknowledge Charles Crane, and Andres Cortez for funding this work under the B61 program. We would also like to express our gratitude to the firing leaders and access control officers that came in late at night to make these tests possible, including Dennis Jaramillo, Dennis Herrera, Becky Oertel, Erica Rock, and Kathy Martinez among others.

11. Data Requests

Videos of the tests as well as various other raw data can be made available on request. Please contact Matt Holmes at mholmes@lanl.gov or 505-665-4107.

12. References

[1] Leininger, L. D., Dickson, P., Gresshoff, M., Holmes, M., Hooks, D. E., et al., "IHE Material and IHE Subassembly Qualification Test; Description and Criteria" *Los Alamos National Laboratory Report: LA-UR-15-29238*, 2021.
[2] "DOE Technical Standard; Explosives Safety" *DOE* 2019.
[3] "DOE Standard Explosives Safety" *U.S. Department of Energy Report: DOE-STD-1212-2019*, 2019.
[4] Tran, T. D., Pagoria, P. F., Hoffman, D. M., Cutting, J. L., Lee, R. S., et al., "Characterization of 2,6- Diamino-3,5- Dinitropyrazine-1-Oxide (LLM-105) as an Insensitive High Explosive Material" *Proceedings of the 33rd International Annual Conference on ICT on Energetic Materials-Synthesis, Production and Application*, Karlsruhe, Germany, 2002.
[5] Hoffman, D. M., Lorenz, K. T., Cunningham, B. and Gagliardi, F., "Formulation and Mechanical Properties of LLM-105 PBXs" *Proceedings of the 33rd International Annual Conference on ICT on Energetic Materials-Synthesis, Production and Application*, Karlsruhe, Germany, 2002.
[6] Pagoria, P. F., Mitchell, A. R., Schmidt, R. D., Simpson, R. L., Garcia, F., et al., "Synthesis, Scale-up and Characterization of 2,6-Diamino-3,5-dinitropyrazine-1-oxide (LLM-105)" *Proceedings of the JOWOG 9*, Aldermaston, England, 1998.
[7] Sigg, D., "Interim Determination - Approval Processes for Qualification of Insensitive High Explosive Materials and Subassemblies", Memorandum, *NNSA*, 8/29/18.
[8] Slape, R. J., "IHE Material Qualification Test Description and Criteria", 1984
[9] Ramsay, J. B. and Popolato, A., "Analysis of Shock Wave and Initiation Data for Solid Explosives" *Proceedings of the 4th International Detonation Symposium*, pp. 233-238, White Oak, Maryland, 1965.
[10] Aviles-Ramos, C., Hobbs, M. L., Parker, G. R., Kaneshige, M. J. and Holmes, M. D., "Validation of a Pressure Dependent PBX 9502 Cookoff Model" *15th International Detonation Symposium*, Vol. 711-720, 2014.
[11] Holmes, M. D., Parker, G. R., Dickson, P., Meyer, B. A. and Schmidt, C. C., "Pressure Dependence of Slow Cookoff Behavior in PBX 9502 Bucket Tests" *Proceedings of the 15th International Detonation Symposium*, pp. 1506-1517, San Francisco, CA, 2014.
[12] Parker, G. R., Holmes, M. D. and Dickson, P., "The Effect of Pressure and Venting on the Slow Cookoff of PBX 9502 in the Intermediate-scale Bucket Test" *Los Alamos National Laboratory Report: LA-UR-13-25716*, 2013.
[13] Parker, G. R., "Quick Look Report for Local Test-55-1 & -2: The Heavily Confined PBX 9502 Cookoff Tests" *Los Alamos National Laboratory* 2015.
[14] Holmes, M. D., Parker, G. R., Broilo, R. M., Heatwole, E. M., Vaughan, L. D., et al., "Hockey Puck Cookoff" *Los Alamos National Laboratory Report: LA-UR-16-22340*, 2016.
[15] Hobbs, M. L. and Kaneshige, M. J., "Ignition Experiments and Models of a Plastic Bonded Explosive (PBX 9502)" *J. Chem. Phys.,* Vol. 140, 2014.
[16] Holmes, M. D. and Parker, G. R., "Gas Generation of Heated PBX 9502" *Los Alamos National Laboratory Report: LA-UR-16-27752*, 2016.
[17] Erickson, M. A. and Holmes, M. D., "PBX 9502 Gas-Generation Throughout Long-Duration Thermal Exposure and Cookoff" *Los Alamos National Laboratory Report: LA-UR-19-21164*, 2019.
[18] Englert-Erickson, M. A., Holmes, M. D., Parker, G. R., Schmidt, C. C. and Meyer, B. A., "Gas Transport in the Insensitive High Explosive PBX 9502" *Propellants, Explosives, Pyrotechnics,* Vol. 45, 10.1002/prep.201900337, 2020.
[19] McAfee, J. M., "The Deflagration-to-Detonation Transition" in *Non-Shock Initiation of Explosives*, *Shock Wave Science and Technology Reference Library*, edited by B. W. Asay, pp. 483-535, Vol. 5, Springer-Verlag, 2010.
[20] Parker, G. R., Heatwole, E. M., Holmes, M. D., Asay, B. W., Dickson, P. M., et al., "Deflagration-to-detonation transition in hot HMX and HMX-based polymer-bonded explosives" *Combustion and Flame,* Vol. 215, pp. 295-308, https://doi.org/10.1016/j.combustflame.2020.01.040, 2020.
[21] Skidmore, C. B. and Butler, T. A., "The elusive coefficients of thermal expansion in PBX 9502" *Los Alamos National Laboratory Report: LA-14003*, 2003.

[22] Jaffe, I. and Price, D., "Determination of the Critical Diameter of Explosive Materials" *ARS Journal,* Vol. pp. 1060-1065, https://doi.org/10.2514/8.6205, 1961.

[23] Tarver, C. M., Goodale, T. C., Shaw, R. and Cowperthwaite, M., "Deflagration-to-detonation transition studies for two potential isomeric cast primary explosives" *6th International Detonation Symposium*, Vol. 231-248, 1976.

[24] Gibbs, T. R. and Popolato, A., *LASL Explosive Property Data*, *Los Alamos Series on Dynamic Material Properties*, edited by T. R. Gibbs and A. Popolato, University of California Press, 1980.

[25] Campbell, A. W., "Diameter Effect and Failure Diameter of a TATB-Based Explosive" *Propellants, Explosives, Pyrotechnics,* Vol. 9, pp. 183-187, https://doi.org/10.1002/prep.19840090602, 1984.

[26] Mott, N. F. and Linfoot, E. H., “A Theory of Fragmentation” in *Fragmentation of Rings and Shells*, pp. 207-225, Springer, 1943.

Appendix A New IHE Qualification Standard

IHE Material and IHE Subassembly Qualification Test Description and Criteria

February 10, 2021
Version 14.9

Editor:
Lara D. Leininger[1]

Authors:
Peter Dickson[2], Micha Gresshoff[1], Matt Holmes[2], Daniel E. Hooks[2], Jon L. Maienschein[1], Gary Parker[2]

Contributors: Bill Andrews[1], Eric N. Brown[2], Alan J. DeHope[1], Anthony Dutton[3], Laurence E. Fried[1], Alex Gash[1], Barry G. Hill[3], Maximillian Hobson-Dupont[1], Constantine A. Hrousis[1], Evan Kahl[1], Michael J. Kaneshige[4], Matt McClelland[1], Tommy J. Morris[2], George E. Overturf[1], Paul D. Peterson[1], Philip J. Rae[2], Chris L. Robbins[1], Jonathan A. Simpson[1], Harry K. Springer[1], Craig M. Tarver[1], Daniel Trujillo[2], Kevin Vandersall[1]

Lawrence Livermore National Laboratory
[2] Los Alamos National Laboratory
[3] Pantex Plant
[4] Sandia National Laboratories

February 10, 2021
Version 14.9
LLNL-TR-679331-REV-1
LA-UR-15-29238

Unlimited Unclassified Release

Disclaimer

Lawrence Livermore National Laboratory is operated by Lawrence Livermore National Security, LLC, for the U.S. Department of Energy, National Nuclear Security Administration under Contract DE-AC52-07NA27344.

Publication Record

Revision	Date	Notes
LLNL-TR-679331 LA-UR-15-29238 (version 13.5)	November 17, 2015 (Updated June 7, 2016)	Initial Release
LLNL-TR-679331-REV-1 LA-UR-15-29238 (version 14.7)	May 14, 2020	• Test details of the Deflagration to Detonation Transition (DDT) experiment specified. • High temperature Shock to Detonation (SDT) experiment temperature setpoint from DDT high temperature experiment, instead of from an additional cookoff test. • No substantive changes to the Skid Test • Number of Bullet Tests reduced from 6 to 3 for each of 2 bullet types. • No substantive changes to IHE Subassembly Definitions
LLNL-TR-679331-REV-1 LA-UR-15-29238 (version 14.8)	August 11, 2020	• Addressed typographical and section numbering errors
LLNL-TR-679331-REV-1 LA-UR-15-29238 (version 14.9)	February 10, 2021	• Bullet Test Configuration updated in the narrative (including Figure 7) to reflect as-shot experimental configuration and materials. • Muzzle velocity clarified • Added reference for test geometry and results (Figure 7 and Figure 10)

February 10, 2021
Version 14.9
LLNL-TR-679331-REV-1
LA-UR-15-29238

Table of Contents

February 10, 2021
Version 14.9
LLNL-TR-679331-REV-1
LA-UR-15-29238

Insensitive High Explosive (IHE) Materials and Subassemblies

As defined in Chapter 16 of the DOE Explosive Safety Standard (DOE-STD-1212), IHE Materials are mass-detonable explosives that are so insensitive that the probability of accidental initiation or transition from burning to detonation is negligible. The test series to qualify an IHE material contains the following elements:

1. Deflagration-to-Detonation Transition (DDT)
2. Shock-to-Detonation Transition (SDT)
3. Skid Test
4. Bullet Test

For explosives that do not meet the qualification criteria of an IHE material, there is a test series to qualify as an IHE subassembly in a smaller, weapon-system relevant, configuration. The IHE Subassembly Qualification Test Series contains the following elements:

1. DDT of individual subassembly materials in relevant, conservative, scales to application
2. SDT material test of the main charge only
3. Skid Test
4. Multiple Bullet Impact Test

The first section of this document defines the DDT, SDT, Skid, and Bullet tests that comprise the IHE Material Qualification Test Series.

The second section of this document describes the tests that are required for the IHE Subassembly Qualification Test Series. These tests are described in more general terms, as some details will depend on the configuration and materials of the specific IHE subassembly being tested.

The qualification and approval process described herein is limited to the Department of Energy (DOE) and nuclear weapons applications.

These definitions were approved by vote of the DOE/NNSA Explosive Safety Committee in May 2016 and are required for any new material or subassembly proposed that is not already noted as approved in DOE-STD-1212.

February 10, 2021
Version 14.9
LLNL-TR-679331-REV-1
LA-UR-15-29238

Section 1

IHE Material Qualification Test Series

1.1. Deflagration-to-Detonation Experiment

1.1.1 Introduction

The purpose of the deflagration-to-detonation test is to demonstrate that an IHE material will not undergo deflagration-to-detonation transition (DDT) under stockpile relevant conditions of scale, confinement, and material condition. Inherent in this test design is the assumption that ignition does occur, with onset of deflagration. The test design will incorporate large margins and replicates to account for the stochastic nature of DDT events.

1.1.2 Underlying Physics

DDT in condensed-phase, inhomogeneous, explosives is a significantly more complex process than shock-to-detonation transition (SDT), comprising a number of distinct steps:

1. Ignition of reaction.
2. Conductive burning, in which the ignition front advances by thermal conduction.
3. Convective burning, in which the ignition front advances by penetration of hot, gaseous, products.
4. Compaction of the unreacted explosive ahead of the ignition front by pressurization due to the reaction products, choking off the convective process.
5. Downstream plug formation.
6. Shock formation at the downstream plug boundary.
7. SDT

This process is dependent on:

1. Decomposition chemistry and kinetics: intrinsic properties that control pre-ignition decomposition, which affect the degree of porosity developed at elevated temperature prior to ignition and, consequently, the compaction characteristics of the material. They also determine deflagration rate as a function of pressure; faster favors reaction build up and shorter run-to-detonation distances.

February 10, 2021
Version 14.9
LLNL-TR-679331-REV-1
LA-UR-15-29238

2. Mechanical properties: rate-dependent intensive intrinsic properties that control deflagration rate as a function of accessible surface area via strain-rate-dependent fracture properties, and also determine compaction and plug formation.

This combination of complex factors puts a quantitative understanding of the phenomenon beyond our current modeling capabilities but, since we understand the trends arising from each factor, we can bound the problem by experimental exploration of worst-case scenarios with a limited number of replicates.

Accordingly, the proposed DDT test is highly conservative in terms of the external (to the explosive) parameters of importance, specifically confinement and charge size. The metric is the absence of transition to detonation in a charge size and geometry that permits a significantly longer run distance, and which is subject to much stronger and more massive confinement, than any configuration of relevance to a nuclear weapon.

1.1.3 DDT Test Configuration and Diagnostics

A representative apparatus is shown in Figure 1, and described as follows:

- Heavily confined explosive samples with long run length.
    - Confinement is provided by a thick-walled steel cylinder (yield strength of the steel to be ~36 ksi (or larger); should be widely-available commercially:
        - 3 inch nominal internal diameter,
        - 2 inch wall thickness, and
        - ~40 inches long to accommodate explosive column, head space, and end caps
    - Both ends are sealed with threaded end caps. End cap shall be 2 inches thick in the axial direction and 1.5 inch thick in the radial direction. Length of thread engagement shall be 4 inches. If threaded end caps are undesirable, alternate closure hardware may be used instead, provided confinement is demonstrated to be equivalent (if alternate end cap design is employed, justification demonstrating confinement equivalence must be approved by the DOE/NNSA IHE Qualification Update Group).
    - One end cap possesses an igniter system, typically comprised of a hot-wire embedded in pyrotechnic. The gap between the ignitor and the explosive column should not exceed ¼ inch to ensure the system can reliably ignite deflagration in the explosive; failure to ignite the explosive does not constitute a "passing". In the event that the igniter fails to ignite deflagration in the explosive, re-ignition may be attempted on the assembly.
    - The other end cap possesses a vent hole; ~1/8 inch diameter. This vent hole permits slow gas products to escape, avoiding quasi-static pre-pressurization of the tube, but is too small of a diameter to provide significant venting when cookoff occurs (a choked flow condition is attained when the explosive deflagrates).
    - Length of the explosive column is 36 inches and shorter than the bore length, to leave an initial axial ullage of ~1/2 ± 0.1 inch. This ullage allows for thermal expansion of the explosive column, permitting porosity to develop that might increase the likelihood of DDT. Alternate ullage lengths are permissible if they meet the intent.

- Additional penetrations of the tube are permissible (e.g. for internal thermocouple or pressure diagnostics) provided they do not compromise the mechanical confinement of the tube. If postmortem analysis reveals failure of confinement at the feedthrough location, the validity of the test confinement must be justified.

- Externally heated tube with external temperatures recorded during the long-duration thermal heating of the assembly, at a rate ≥ 0.25 Hz (the temperature rise during dynamic event does not need to be resolved).
- Test may be executed with tube in any orientation (horizontal, igniter on top, igniter on bottom). If the test is oriented with the igniter on top, care must be taken that explosive successfully ignites even if internal slumping takes place during the thermal conditioning and there is a gap between the ignitor system and the explosive column.
- Two material states examined are (1) typical charge density and (2) surrogate damaged material utilizing pressing prills (molding powder) of the candidate material.
  1. Consolidated explosive can be in the form of multiple stacked uniaxially pressed pellets, provided the pellet density is within ±1% of production density material. The diametral clearance between explosive pellets and bore at ambient temperature shall be small enough so that thermal expansion during heating develops an interference fit once the explosive reaches 10°C below the critical temperature for the experiment, with consideration given to the Coefficient of Thermal Expansion (CTE) of the explosive being tested. This interference fit prevents gas flow between the explosive and the wall of the tube, so burning will progress through the bulk explosive and not at the edges.
  2. Pressing prills (molding powder) shall be loaded into the bore via “pouring” with no additional packing pressure applied. This assembly method will achieve a “pour density” test configuration, which constitutes the lowest handling density of material and a worse-case scenario with regards to surface area available for deflagration. Pour density attained shall be reported as part of the test record and will be calculated from the mass of the material used and the nominal volume of the bore.
- The IHE candidate material is evaluated in two configurations:
  1. In one configuration, the explosive self-ignites from heating, similar to a cookoff test. (Although the igniter system is not required for this test configuration, any through holes in the non-vented cap end of the tube shall be plugged.). This configuration is used to establish a “critical temperature”, T_c.
  2. In a second configuration, after reaching a set elevated temperature, which is slightly below the established critical temperature, deflagration is ignited by a donor pyrotechnic.
- Diagnostics:
  - External tube temperatures (e.g. thermocouples).
  - Post-reaction examination of the confinement tube, particularly fragment size distribution.
  - Velocimetry (e.g. PDV) on the tube wall close to the vented end to quantify the presence (or lack of) detonation at the end of the tube. PDV diagnostics may be optional if the occurrence of DDT can be successfully ascertained by comparison with deliberately-detonated tubes (e.g. postmortem analysis of fragments).

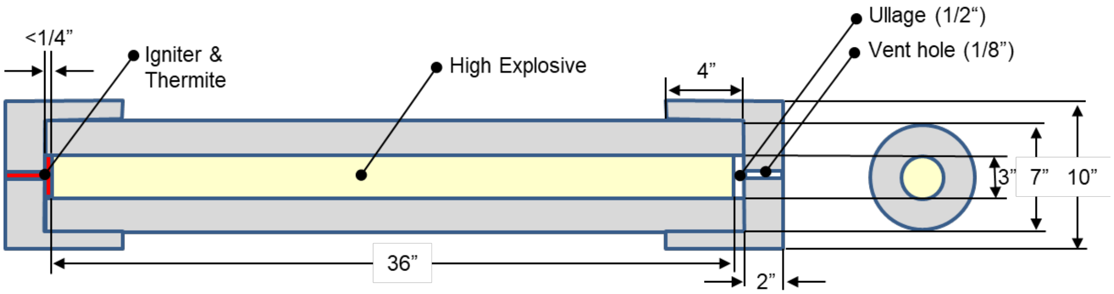


Figure 1: Conceptual configuration of IHE Deflagration-to-Detonation Transition (DDT) IHE experiment.

1.1.3.1 Test Conditions

First test series (slow cook-off ensures ignition at the center of the charge):

- Production density explosive is heated ~20˚C/hr until self-ignition occurs. Intent of heating rate is to achieve no more than 10˚C radial temperature difference.
- The control location for temperature shall be a measurement of the external surface of the central tube, at the midpoint of the long dimension of the tube. The temperature measurement will not be in contact with a heating element, shall be adequately insulated from ambient air conditions, and adhered to the metal to ensure that the measurement accurately represents the surface temperature of the tube.
- The temperature of this control thermocouple when explosion occurs will be designated Tc (critical temperature) for the purpose of this experiment. It is understood that this critical temperature is not directly indicative of the explosive temperature necessary to induce self-ignition, but rather as a fiducial reference for conducting subsequent experiments. Designating a critical temperature using exterior thermocouples provides a test method that avoids the challenge of diagnosing internal temperatures without compromising the confinement of the assembly.
- This test configuration is identically repeated twice more for a total of three tests. The lowest Tc obtained of the three tests is used as the Tc for subsequent testing.
- External temperature difference is measured along the length of the central tube and shall not exceed 10 ˚C during heating.

Second test series:

- Production density explosive is heated at the same ramp rate of ~20˚C/hr to 10˚C below Tc, then promptly ignited with a pyrotechnic composition.
- If the final recorded temperature is higher than 10˚C below Tc, the test remains valid; the final recorded temperature must be ≥ [Tc-10˚C].

Third test series:

- Pour density molding powder is tested identically (heated at ~20˚C/hr to 10˚C below Tc, then promptly ignited with a pyrotechnic composition).
- If the final recorded temperature is higher than 10˚C below Tc, the test remains valid; the final recorded temperature must be ≥ [Tc-10˚C].

1.1.3.2 Number of Tests

Three tests at each test series (9 total). As mentioned above, all three repeats of the first configuration are performed first in order to determine the lowest Tc; that Tc is used for the remaining two series. The purpose of the triplicate execution of the second and third configurations is to establish a measure of statistical repeatability. If substantive variations in test outcome are observed—even if no test exhibits DDT—the validity of the test series must be reviewed by the DOE/NNSA IHE Qualification Update Group.

1.1.3.3 Quantity of Explosive Required

- ~8 kg per production density explosive test.
- ~5 kg per molding powder explosive test.
- ~63 kg for nine tests.

1.1.3.4 Criteria for Qualifying as IHE

No development of a detonation wave within the tube length in any test as confirmed by post-test examination of the tube and/or by fielding velocimetry.

- If velocimetry diagnostics are not fielded, two additional deliberate detonation tests must be performed to provide a baseline against which to compare the qualification test results. One tube is deliberately detonated with production-density explosive, the other with the pour density molding powder. For both tests, a section of central tube ≥ 1 ft long (otherwise with the same bore diameter and wall thickness) will be filled at one end with 6 inches of explosive material. A detonator and booster will be placed in contact with the inside surface of the explosive fill and deliberately detonated. No end caps are required. The failure morphology of the tube obtained from these deliberate detonation baseline tests can be used in comparison with the qualification testing to establish whether detonation occurred.

OR

- Absence of DDT may be diagnosed with velocimetry data.

1.2. Shock-to-Detonation Experiment

1.2.1 Introduction

The purpose of the shock-to-detonation experiment is to demonstrate that the IHE will not undergo shock-to-detonation transition (SDT) under a defined shock stimulus at ambient temperature, which differentiates the SDT behavior of IHEs from the SDT behavior of Conventional High Explosives (CHEs). Note that any explosive, IHE or CHE, must undergo SDT at some shock stimulus for a nuclear weapon to function as designed.

In addition to the defined ambient-temperature shock stimulus, an additional SDT experiment is required at high temperature, to show that the explosive is not excessively sensitized by exposure to high-temperature conditions.

The ambient-temperature threshold shock stimulus was developed based on consideration of the shock sensitivity of a set of CHEs and currently recognized IHEs (Gresshoff, 2018). Figure 2 shows the shock sensitivity of CHEs and IHEs represented as a threshold SDT pressure as a function of shock duration.

Figure 2 is based on run-to-detonation, or Pop-Plot, data for TATB-based (LX-17, PBX 9502, and UF-TATB) and HMX-based (LX-04, PBX 9501, LX-07-2, and LX-10) high explosives scaled to the shock initiation threshold based on short-pulse initiation data for LX-17 and LX-04 (Gresshoff, 2018). There is some uncertainty in this scaling; however, the shock duration for the SDT threshold was chosen with this in mind and was necessary as the run-to-detonation distance is unknown for a future candidate IHE. As pressure is decreased, the shock duration required for SDT increases until a pressure is reached where there is no SDT regardless of the shock duration. HMX and TATB cut-offs are estimated at ~1.5 and ~7.5 GPa respectively for the HEs evaluated in this study and published in the literature. It is expected that SDT does not occur below these pressures, even for very long shocks. The figure indicates the SDT criterion for a sustained shockwave (3 μs duration) is 3.5 GPa.

Previous work on IHE Qualification of TATB (PBX 9502, LX-17, and UF-TATB) show data from Pantex Plant (Slape, 1984) which suggest that IHE qualification with the No. 8 Blasting Cap detonator was performed on both molding powder and “compacted” parts at nominal density. Although it was never written in DOE-STD-1212 (which prescribes TB 700-2 protocol for transportation and storage with molding powder), this history suggests a precedence for short-duration, high pressure, Taylor wave-type, loading of pressed parts as a component of the material definition. Hydrocode calculations of the Pantex Modified NOL Card Gap test showed that the upper limit of output for a Taylor wave into Explosive D is approximately 5.3 GPa. The lower limit of duration available for a gas gun flyer plate design is approximately 0.5 μs duration (cap duration is expected to be longer, but a Taylor wave). Therefore, the criterion for short pulse shockwave is prescribed to be 5.3 GPa at 0.5 μs and noted on Figure 2.

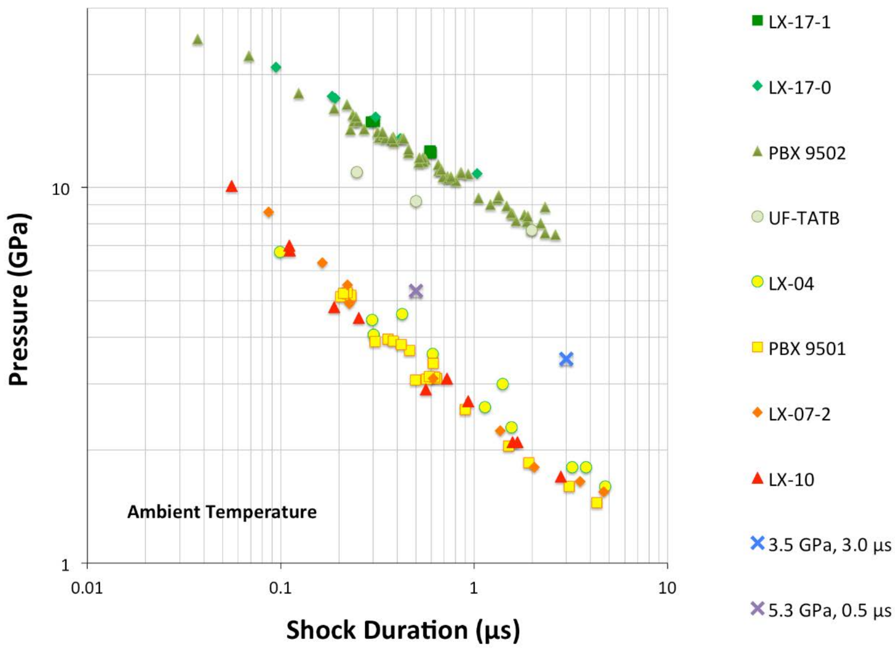


Figure 2. Shock sensitivity of several DOE explosives scaled from Pop-Plot data, showing the separation in behavior between IHEs and CHEs. The TATB-based IHEs (LX-17, PBX 9502, and UF-TATB) form a family with significantly lower shock sensitivity than the HMX-based CHEs (LX-04, PBX 9501, LX-07, and LX-10). The SDT criterion for IHEs is no evidence of detonation for a long-pulse (3 μs duration) of 3.5 GPa and a short-pulse (0.5 μs duration) of 5.3 GPa.

A second experimental series is required to evaluate SDT at high temperature. Virtually all known explosives are sensitized to SDT at high temperatures. It is important that the degree of sensitization to shock not be so high that the heated explosive represents a severe SDT hazard. The hazard is likely worse at the highest temperature where the explosive will survive, and the risk is that the explosive is extremely shock sensitive (e.g. an explosive that passes that SDT criteria at ambient, but recovers primary-like shock sensitivity at high temperatures is undesirable). The shock criterion for a heated test is substantially lower than criterion for the ambient temperature test. High-temperature shock sensitivity data for some IHEs and CHEs are shown in Figure 3 (Gresshoff, 2018). Because short-pulse data is not widely known for HEs at temperature, the data in the graph is still in the standard “Pop-Plot” format revealing pressure and run distance to detonation.

Also shown in Figure 3 is the new IHE criterion for high-temperature shock sensitivity – absence of shock-to-detonation transition with a 1.5 GPa shock sustained for at least 3 μs. The high-temperature testing must be done at a temperature that involves the effect of phase changes or other physical changes. For this reason, the test temperature is defined as the temperature 10°C below that which the explosive is expected to thermally explode, which will be a worst-case test for thermal sensitization.

February 10, 2021
Version 14.9
LLNL-TR-679331-REV-1
LA-UR-15-29238

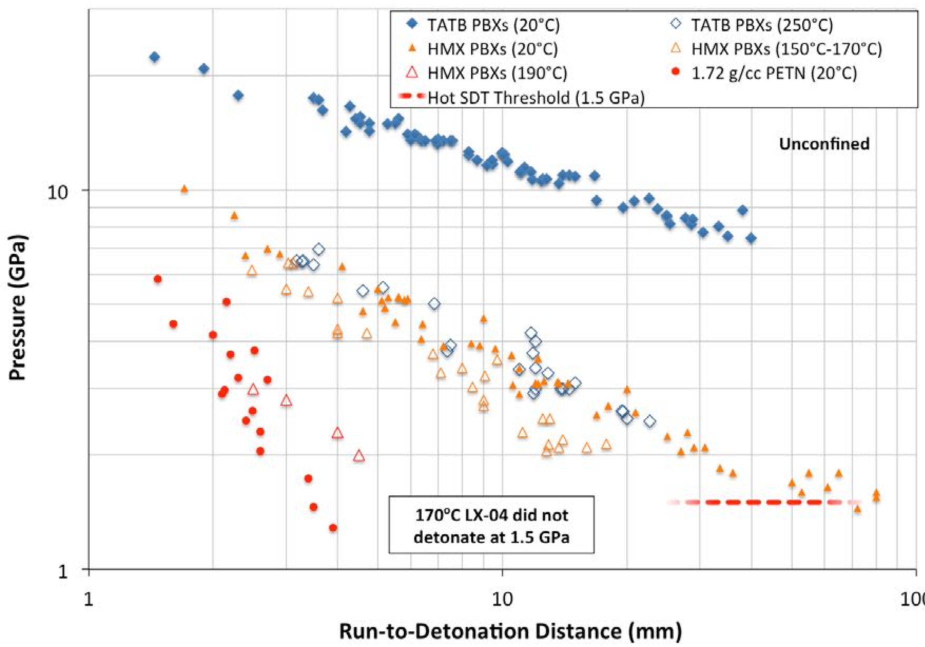


Figure 3. Shock sensitivity of several DOE explosives at high temperatures. The elevated-temperature SDT criterion of 1.5 GPa is shown as a dotted line as run-to-detonation distance is unknown in future candidate IHEs.

1.2.2 Underlying Physics

In the accepted understanding of shock-to-detonation transition (SDT) in composite solid explosives, interaction of the shock front with voids, interfaces, or other irregularities in the solid results in development of localized hot spots. If the shock is sufficiently strong and long-lasting, these hot spots react, coalesce, and release chemical energy fast enough to accelerate the shock wave until it forms a detonation. If the shock is too low in magnitude or duration, the hot spots may not react, or may quench before coalescing, and transition to detonation does not occur.

In addition to shock magnitude and duration, other factors are very important in SDT. The shock duration determines the time until a rarefaction from the rear of the sample reduces the shock pressure and may quench the reaction. Rarefaction waves from the side of explosive samples will have a similar effect, with the rarefaction penetrating farther from the edge as the shock travels from the impact surface. Shocks driven by small-diameter impactors similarly have rarefaction waves from the side that will quench the reaction. Therefore, size of explosive sample and diameter of the impactor driving the shock wave are important. If the shock is not planar or is not parallel to the explosive surface, these interactions are even more complex. If the shock wave at a surface is reflected back into the sample by a higher-impedance material, this also may have a strong effect on the SDT response.

To make the IHE test for SDT as unambiguous and reproducible as possible, it is specified as a 1-dimensional planar shock input with long duration. The explosive sample diameter and length are specified to avoid the effect of rarefactions from the side, while also allowing enough distance for the shock to run before side rarefactions come into play.

The propagation rate of the shock or reaction front provides a clear delineation between an unreacted shock and a detonation wave. Diagnostics are embedded in the explosive sample to measure either pressure or particle velocity, *in situ*, and measure if the shock wave is building to a detonation or is failing. The use of such diagnostics is an important element of these tests, as a reacting shock wave that may not have reached detonation conditions is a quite different response than an unreacted, or failing, shock front.

Sensitization of explosives at high temperature is driven by physical transformations in the explosive. For TATB plastic-bonded explosives, the shock sensitivity at 250°C is caused by the irreversible ratchet growth with formation of additional voids that sensitize the explosive to shock; when TATB explosives are physically confined, the shock sensitivity is significantly reduced. For HMX plastic-bonded explosives, the shock sensitivity is only slightly increased by heating to 150°C; the large increase in sensitivity at 190°C is caused by the beta-to-delta phase transition in HMX with the resultant formation of additional voids. To evaluate a candidate IHE, testing must be done at a sufficiently high temperature to include the effect of phase changes or other physical changes. The worst-case conditions are those in which the explosive is heated just below the temperature at which it will thermally decompose. This temperature is dependent on the thermal stability of the explosive, and on the configuration (e.g., size) of the explosive sample, and therefore the test temperature cannot be defined *a priori*. Instead, it is defined as the temperature 10°C below that at which the explosive will thermally explode in a relevant configuration.

1.2.3 SDT Test Configuration and Diagnostics

- Use gun to achieve reproducible 1-D planar shock into sample.
- Ambient temperature test:
    - 3.5 GPa, >3.0 µs
    - 5.3 GPa, >0.5 µs
- High temperature test:
    - Explosive is heated at a ramp rate of ~20˚C/hr to a set point of [Tc-10 ˚C], where Tc is the temperature determined in the DDT cook-off test as measured on the boundary of the sample.
    - 1.5 GPa, >3.0 µs
- Explosive sample diameter and length sufficient to ensure 1-D shock:
    - diameter: ~60-90 mm (~2.5-4 inches).
    - length: ~30-45 mm (~1-1.5 inches).
- Explosive density: within the production range for the application.

- Diagnostics:
    - Embedded gauges (pressure or particle velocity) at several distances from the shock front.
    - Other standard diagnostics to measure impact velocity.
- To achieve shock pressures and durations for the 1D collision of a teflon impactor (2.15 g/cc, C_o=2.08 mm/μs, S_1=1.62) on an LX-17 IHE sample (1.9 g/cc, C_o=2.5 mm/μs, S_1=2.1) at room temperature (configuration shown in Figure 4):
    - 3.5 GPa for 3 μs:

    6 mm thick flyer at 1 km/s
    - 5.3 GPa for 0.5 μs:

    1 mm thick flyer at 1.5 km/s

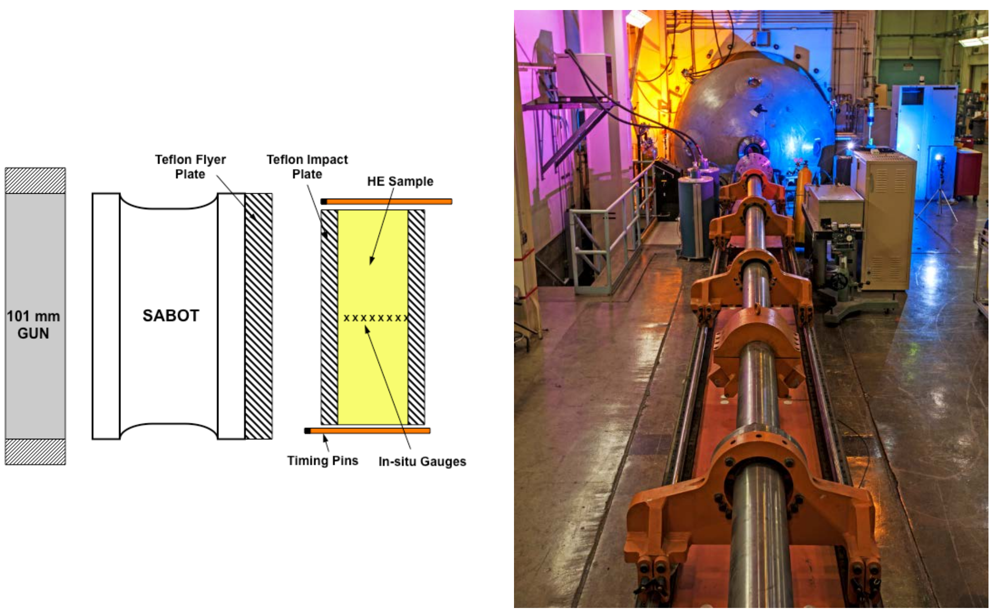


Figure 4. Example of SDT test configuration in the 100 mm gun at LLNL's High Explosive Application Facility (HEAF). Other similar configurations will give the same type of data and are equally acceptable. Elevated-temperature shock tests require heaters and thermocouples integrated into the target assembly.

1.2.3.1 Test Conditions

- Temperature
    - Ambient temperature: ~ 25°C.

   - High temperature: 10°C below the thermal explosion temperature for the explosive from the DDT cook-off experiment.
- Shock input to explosive with symmetric flyer/impact surface.
- Embedded diagnostics.

1.2.3.2 Number of Tests

- Three replicate tests at each temperature.

1.2.3.3 Quantity of Explosive Required

- ~600 g per test.
- ~1,800 g for three tests at each temperature.
- ~3.6 kg total.

1.2.3.4 Criteria for Qualifying as IHE

- No development of detonation wave in the explosive as shock progresses through the sample.
- Reaction wave, if any, is failing as the end of the sample is approached, as shown by the pressure or particle velocity gauges.

1.3. Skid Test

1.3.1 Introduction

The purpose of the skid test is to show that bare billets of explosive will not react with significant violence when subjected to a very severe drop environment, far worse than is anticipated in any actual handling accident.

For this test, which is a worker safety test, the acceptance criteria are based on worker safety concerns rather than detonation. As described below, the worst-case response for an explosive that has passed the skid test is non-violent explosive reaction.

The pendulum apparatus used in this skid test was first developed by Los Alamos National Laboratory in 2013 (Parker et al., 2020) and was conceived and designed to capture the underlying physics of reaction which had only previously been observed in "outlier data" as reported from the standard skid tests (Slape, 1984; Garrow, 2015). The new pendulum configuration allows exquisite control of the strike surface location, angle, and drop height such that potential reaction can be imaged to quantify the hazard and the experiment is highly repeatable. The apparatus has been designed to provide equivalent loading to the previously used vertical free-fall apparatus, with improved diagnostics.

1.3.2 Underlying Physics

The physical mechanisms governing explosive response in the skid test are very complex. Impacts such as those encountered from any conceivable drop height are incapable of driving a shock-to-detonation response. Ignition and deflagration is the worst possible outcome. The initial impact of an explosive causes compression and/or fracture with simultaneous conversion of mechanical energy to heat by frictional heating, which is generally grit-mediated. If the thermal energy is sufficient to ignite the explosive, and depending on the surface area that is produced by the fracture that may then become incorporated into the reaction, the ensuing response may range from a few points of light, to a rapid deflagration, to a detonation. If the DDT test described previously has been successfully completed before the skid test is executed, then the most violent response of a detonation is not possible, and the worst case is a rapid deflagration.

1.3.3 Skid Test Configuration and Diagnostics

- Pendulum skid impact test based on the new LANL Skid Test apparatus (Parker et al., 2020) shown in Figure 5
- Hemispherical sample, 28 cm diameter, of production density explosive
- Target surface will be gritty glass or steel.
    - Grit particles must be loose or weakly bonded such that they break free during impact.

  - Level of grit (silica sand, mean diameter ~600 µm) should be sufficient to cover the strike surface, while still providing space between grit (typical coverage: areal density ~$2x10^5$ particles/m^2) (Heatwole et al, 2015)

- Diagnostics: High-speed video side-on to impact plane and through target plate if transparent

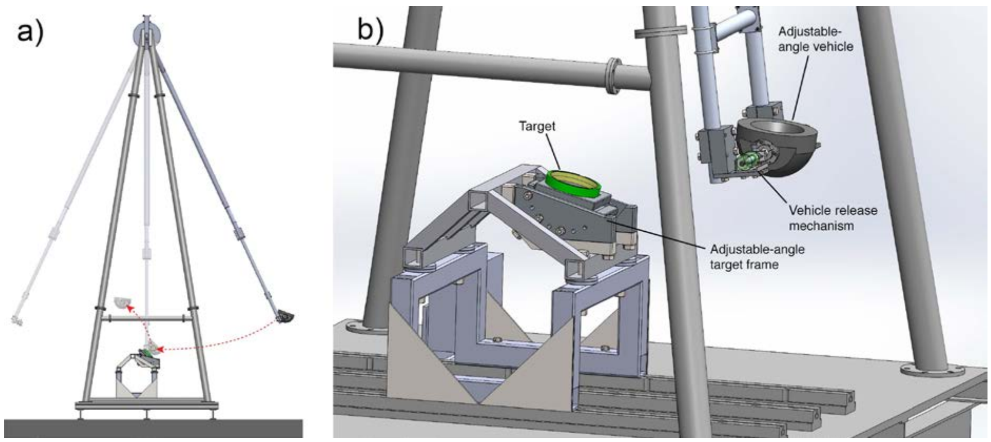


Figure 5. Pendulum skid impact test based on the new LANL Skid Test apparatus. (a) arm length = 15 ft (b) hemispherical charge rests in cradle, free to escape (bounce) upon contact with target.

1.3.3.1 Test Conditions

- Initial test configuration: Production machined hemisphere at ambient temperature
- Impact angle of 45˚
- Initial equivalent drop height of 12 ft. "Equivalent drop height" is the height at which the pendulum must be released in order to achieve an impact velocity that is equal to the impact velocity attained during vertical free-fall, i.e. $v = \sqrt{(2gh)}$. A 12 ft drop is a representative yet conservative worse-case height for handling accident scenarios involving workers manipulating a bare charge.

1.3.3.2 Number of Tests

- Three at 12 foot-equivalent drop height.

1.3.3.3 Quantity of Explosive Required

- ~10 kg per hemispherical charge.
- ~30 kg for three tests.

1.3.3.4 Criteria for Qualifying as IHE in the Skid Test

Reaction criteria (Note: These levels have been modified from levels in the original skid test which ranged from "0" for "no reaction" to "6" for "full detonation" (Garrow, 2015)). Image panels of the various reactions are shown in Figure 10 from Parker, et al. (2020):

- Reaction 0 is acceptable:
  - No visible smoke. No scorching of explosive surface. Video may show glowing abrasive particles from target surface.
- Reaction 1 is acceptable:
  - Visible smoke. Non-propagating, luminous ignition sites may be visible. Scorching of the explosive surface. No luminous flames are visible in high-speed videography from a side view.
- Reaction 2 is not acceptable:
  - Propagating, luminous flames are visible from high-speed videography. Postmortem examination reveals partial or complete disintegration of the explosive contact surface due to cracking induced by explosive reaction.

- The above criteria apply regardless of fracture of the explosive test object.
  - Occurrence of Reaction 2, or reaction violence exceeding Reaction 2, in any of the tests performed in the series, including tests where the charge fractured, disqualify the material as an IHE.

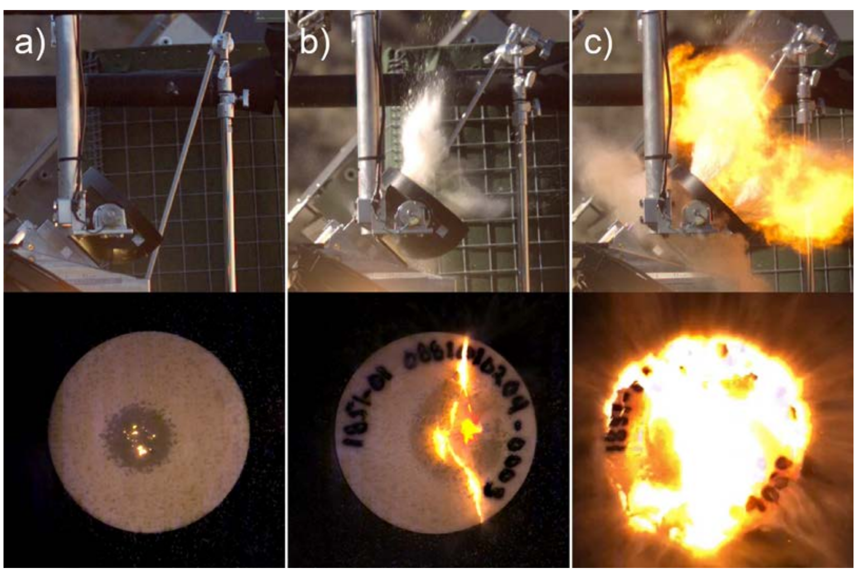


Figure 6. Examples of skid test reaction levels with a smaller, scaled, explosive charge. Three image pairs showing synchronous views from the side and through transparent impact surfaces: (a) Reaction 1, non-propagating luminous ignition sites, (b) Reaction 2, flame propagation into cracks, no fireball, and (c) Reaction 2, flame propagation and fireball.

1.4. Bullet Test

1.4.1 Introduction

The purpose of the bullet test is to show that an IHE does not react violently when impacted by a bullet under the conditions described below. This is a demonstration that the IHE is relatively unreactive to this type of stimulus and is not intended to prove that the IHE will not react to any sort of bullet or related stimulus. The ammunition selected is representative of threats to which the IHE will be exposed during its lifecycle but does not represent the worst possible case. The configuration represents the likely worst-case path of least resistance. Figure 10 shows an example of the response from this test for both HMX-based and TATB-based explosives.

1.4.2 Underlying Physics

Explosive response to the impact from a bullet is very complex. Typically, the bullet does not impart a shock to the explosive in such a way to cause shock-to-detonation transition, but instead provides input of mechanical and thermal energy to the explosive. The mechanical energy of the bullet impacting and tearing through the explosive is converted to thermal energy by the thermomechanical response of the explosive, and thermal energy from the hot bullet is deposited as the bullet travels through. This thermal energy may cause the explosive to ignite, and then may eventually lead to an explosion.

The mechanical response of the explosive is dependent on its configuration and confinement. The experimental configuration shown in Figure 7 offers a geometry representative of both CHEs and IHEs in their intended applications.

1.4.3 Bullet Test Configuration and Diagnostics

The test configuration is shown in Figure 7 (from Leininger et al. 2021).

- Explosive sample is contained in a steel fixture with a tantalum alloy front plate, steel inner plate, and aluminum back plate.
- Bullets are shown in Figure 8 and Figure 9, and are 50 caliber, armor piercing, and military ball rounds.
- Bullet enters the sample through the front plate and exits through a plate-foam-plate stack-up.
- Diagnostics:
    - Include a method to measure the bullet velocity.
    - High-speed imaging to observe the target response for at least 10 seconds.

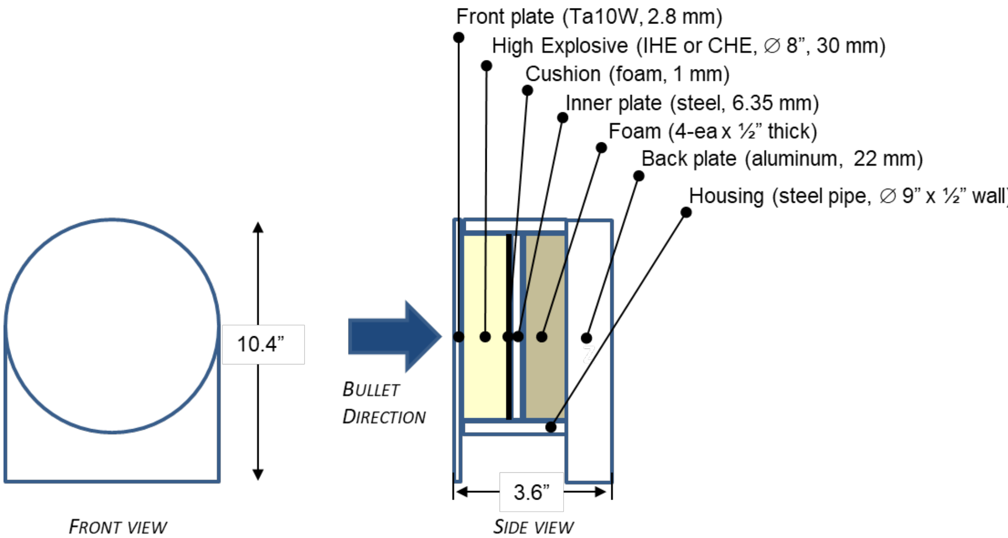
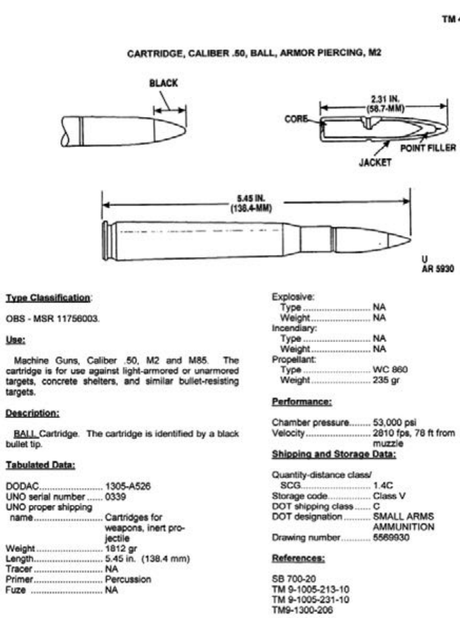


Figure 7. Conceptual configuration of IHE Qualification Bullet Test



Type Classification:

OBS - MSR 11756003.

Use:

Machine Guns, Caliber .50, M2 and M85. The cartridge is for use against light-armored or unarmored targets, concrete shelters, and similar bullet-resisting targets.

Description:

BALL Cartridge. The cartridge is identified by a black bullet tip.

Tabulated Data:

DODAC.......................... 1305-A526
UNO serial number 0339
UNO proper shipping name.......................... Cartridges for weapons, inert projectile
Weight.......................... 1812 gr
Length.......................... 5.45 in. (138.4 mm)
Tracer .... NA
Primer.......................... Percussion
Fuze .... NA

Explosive:
Type .... NA
Weight.......................... NA
Incendiary:
Type .... NA
Weight.......................... NA
Propellant:
Type .... WC 860
Weight.......................... 235 gr

Performance:

Chamber pressure......... 53,000 psi
Velocity.......................... 2810 fps, 78 ft from muzzle

Shipping and Storage Data:

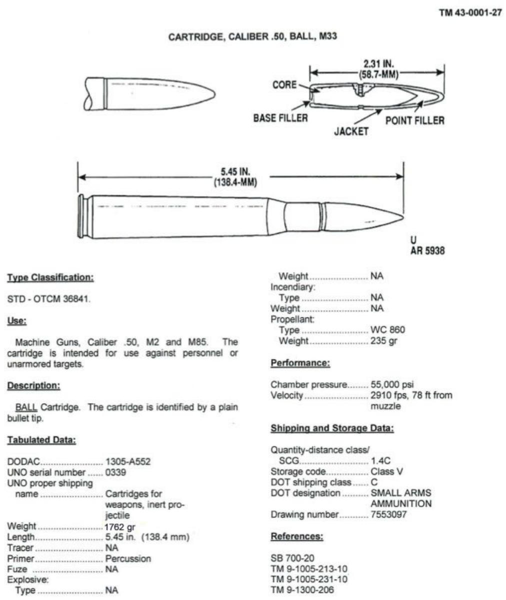
Quantity-distance class/ SCG.......................... 1.4C
Storage code................ Class V
DOT shipping class C
DOT designation .... SMALL ARMS AMMUNITION
Drawing number........... 5569930

References:

SB 700-20
TM 9-1005-213-10
TM 9-1005-231-10
TM9-1300-206

Figure 8. 50-caliber armor piercing round.

February 10, 2021
Version 14.9
LLNL-TR-679331-REV-1
LA-UR-15-29238



TM 43-0001-27

CARTRIDGE, CALIBER .50, BALL, M33

2.31 IN.
(58.7-MM)
CORE
BASE FILLER
JACKET
POINT FILLER
5.45 IN.
(138.4-MM)
U
AR 5938

Type Classification:

STD - OTCM 36841.

Use:

Machine Guns, Caliber .50, M2 and M85. The cartridge is intended for use against personnel or unarmored targets.

Description:

BALL Cartridge. The cartridge is identified by a plain bullet tip.

Tabulated Data:

DODAC........................ 1305-A552
UNO serial number 0339
UNO proper shipping
name .... Cartridges for weapons, inert projectile
Weight........................ 1762 gr
Length........................ 5.45 in. (138.4 mm)
Tracer .... NA
Primer........................ Percussion
Fuze .... NA
Explosive:
Type .... NA
Weight........................ NA
Incendiary:
Type .... NA
Weight........................ NA
Propellant:
Type .... WC 860
Weight........................ 235 gr

Performance:

Chamber pressure........ 55,000 psi
Velocity........................ 2910 fps, 78 ft from muzzle

Shipping and Storage Data:

Quantity-distance class/
SCG........................ 1.4C
Storage code............... Class V
DOT shipping class C
DOT designation .... SMALL ARMS AMMUNITION
Drawing number........... 7553097

References:

SB 700-20
TM 9-1005-213-10
TM 9-1005-231-10
TM 9-1300-206

Figure 9. 50-caliber ball round.

1.4.3.1 Test Conditions

- Ammunition: 50 caliber armor piercing and 50 caliber military ball round.
- Muzzle velocity: standard for each type, no less than 2700 ft/s and no more than 3050 ft/s
- One bullet per test.
- Explosive sample:
    - Diameter: 8 inches (~200 mm)
    - Thickness: ~1 inch (30 mm)
    - Density: within the specified range for the application.
        - Main charges are generally 96-98% TMD.
        - Boosters are generally 92-95% TMD.

1.4.3.2 Number of Tests

- Three replicates with each bullet type (six tests total).

1.4.3.3 Quantity of Explosive Required

- ~ 1.8 kg per test.
- ~ 11 kg total.

1.4.3.4 Criteria for Qualifying as IHE

- Burn: smoke and/ or visible light is acceptable, burning reaction can completely consume material. Assembly may be distorted, and surfaces blackened. Any level of damage beyond that is a failure. If the assembly is fragmented, that is a failure.
- Panels of pass and fail are in Figure 10 (based on results reported in Leininger et al. 2021).

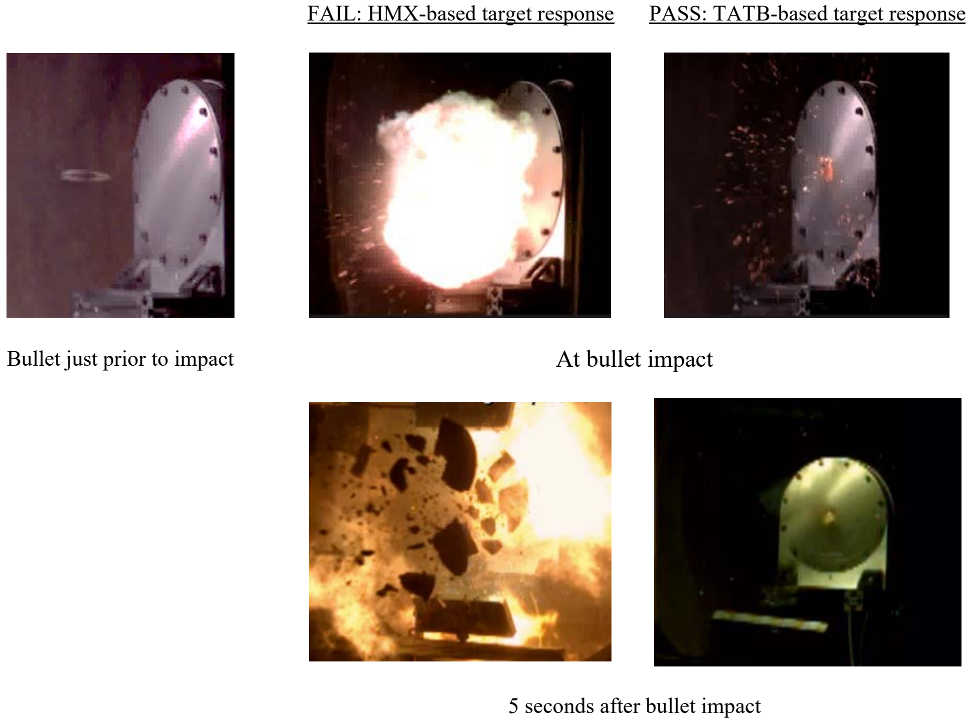


Figure 10. The bullet impact test distinguishes between the reaction violence of an HMX-based explosive and TATB-based explosive to the impact with a 50 caliber armor-piercing round. In this case, the HMX-based explosive fails to meet the IHE criteria. The visible light/reaction at impact is acceptable, however the violent disassembly of the undetonated HE constitutes a failure.

February 10, 2021
Version 14.9
LLNL-TR-679331-REV-1
LA-UR-15-29238

Section 2

IHE Subassembly Qualification Test Series

This section outlines a general plan to qualify IHE subassemblies that contain explosives that are not qualified as IHE materials. In general, this will occur when it is desired to have an IHE subassembly that consists of a main charge of IHE qualified materials with CHE boosters and/or detonators. However, it is also possible that the main charge be a material that has not passed the IHE material qualification tests outlined in Section 1, provided it qualifies to the same criteria at a system-relevant scale (as described herein), and it passes the SDT criterion for an IHE material at both ambient and heated conditions.

While this document provides an outline of the expectations for IHE subassembly qualification, this is an outline to aid in the development of a test plan for approval by the DOE/NNSA Explosives Safety Committee in consultation with the DOE/NNSA IHE Qualification Update Group. DOE-STD-1212, Chapter 16, Section 16.6 “IHE Subassembly Qualification Process” outlines the procedure for submitting a test plan, committee review procedures, and submission requirements. The test plan must consider worst-case configurations for testing.

2.1. Deflagration-to-Detonation Transition Experiment

For cases where the main charge is composed of IHE qualified materials, using booster, detonator, or other materials that are not IHE, it is a requirement to demonstrate that the materials that are not IHE cannot undergo DDT on a scale that is conservative to its relevant application in the subassembly.

For cases where it is desired to use a main charge that is not an IHE qualified material, but is smaller than was imagined in the material definition from the previous section, the main charge material must also be subjected to and pass a DDT test at the scale of use plus a conservative margin of scale and confinement consistent with the IHE materials test scale outlined in Section 1.1.

Each non-IHE material to be used shall be qualified by testing it in a scaled version of the DDT test. Each material will be tested in this configuration in a scale that is the actual scale of use plus a conservative margin in dimensions and confinement. All materials in the subassembly must pass this test individually for the subassembly to qualify as an IHE subassembly. No evidence of DDT may be observed in any test. Three replications of each test are required.

2.2. Shock-to-Detonation Transition Experiment – Main charge only

In order for the subassembly to qualify as an IHE subassembly, the main charge material must pass the identical SDT test as described in Section 1.2, for both ambient and heated configurations, with the same criteria for a passing result. Booster and detonator materials are not subjected to the SDT criteria to be consistent with previous test requirements.

2.3. Skid Test

Skid testing will be performed as above in Section 1.3, except that the assembly will be dropped for impact in the worst possible configuration - on the booster surrounded by main charge material consistent with the actual weapon configuration, with or without detonators. Three tests are required with drops at 45 degrees from 12 ft, with no observation of violent reaction (based on criteria described in Section1.3.3).

2.4. Multiple Bullet Impact Test

Bullet testing will be performed on the assembly, and in this case, the configuration of the target material will be designed to present a worst-case, path of attack, for the weapon subassembly. The test specimen geometry may or may not be the same as described in Section 1.4. If the path of attack includes a booster, then that booster must be included in the test. Threat is a three-round burst of NATO-7.62 mm (0.3 inches) ammunition. The passing criterion is to exhibit no violent reaction (based on criteria described in Section 1.4.3.4) when subjected to the threat. Three replicate tests are required.

February 10, 2021
Version 14.9
LLNL-TR-679331-REV-1
LA-UR-15-29238

References

1. Cheung, H., et al., “Explosive Initiation,” LLNL Report UCRL-76578, June 18, 1975.
2. Chidester, S.K., et al., “Shock Initiation Experiments on PBX 9501 Explosive at Pressures Below 3 GPa with Associated Ignition and Growth Modeling,” *Shock Compression of Condensed Matter*, AIP Conference Proceedings 955, 2007, pp. 903-906.
3. Christensen, J.S., et al., “Probabilistic Shock Threshold Development for LX-17,” *15th International Detonation Symposium*, Office of Naval Research ONR 43-280-15, San Francisco, CA, 2014, p. 639.
4. Dallman, J.C., and J. Wackerle, "Temperature-Dependent Shock Initiation of TATB-based High Explosives," *10th International Detonation Symposium,* Office of Naval Research Report 3395-12, Boston, MA, 1993, pp. 130-138.
5. Dick, J.J., et al., "The Hugoniot and Shock Sensitivity of a Plastic-Bonded TATB Explosive PBX 9502," *Journal of Applied Physics* 63(10), 1988, pp. 4881-4888.
6. Forbes, J.W., et al., “The Effects of Confinement and Temperature on the Shock Sensitivity of Solid Explosives,” *11th International Detonation Symposium*, Office of Naval Research ONR 33300-5, Snowmass, CO, 1998, p. 145.
7. Garrow, M.T., “Skid Testing of Modified As-Pressed Universal Hemispheres,” Pantex Report PXRPT 16-03 Revision 0, October 19, 2015.
8. Gibbs, T.R. and A. Popolato (ed.), *LASL Explosive Property Data*, University of California Press, 1980, p. 370.
9. Green, L.G., et al., “Shock Initiation of LX-07-2 and LX-10-0,” LLNL Report UCRL-50851, 1970.
10. Gresshoff, M., “Insensitive High Explosive Shock-to-Detonation Transition Criteria,” *16th International Detonation Symposium*, Cambridge, MD, 2018.
11. Gustavsen, R.L., et al., “Embedded Electromagnetic Gauge Measurements and Modeling Shock Initiation in the TATB Based Explosives LX-17 and PBX 9502,” *Shock Compression of Condensed Matter*, AIP Conference Proceedings 620, Atlanta, GA, 2001, pp. 1019-1022.
12. Gustavsen, R.L., et al., “Shock initiation of new and aged PBX 9501,” *12th International Detonation Symposium*, San Diego, CA, 2002, pp. 530-537.
13. Gustavsen, R.L., et al., “Measurement of Shock Initiation in the Tri-amino-tri-nitro-benzene Based Explosive PBX 9502: Wave Forms from Embedded Gauges and Comparison of Four Different Material Lots,” *Journal of Applied Physics* 99, 2006, pp. 114907-1.
14. Gustavsen, R.L., et al., “Extended Run Distance Measurements of Shock Initiation in PBX 9502,” *Shock Compression of Condensed Matter*, AIP Conference Proceedings 955, 2007, pp. 915-918.
15. E. Heatwole, G. Parker, M. Holmes, P. Dickson, “Grit-mediated frictional ignition of a polymer-bonded explosive during oblique impacts: Probability calculations for safety engineering), Reliability Engineering and System Safety 134 (2015) 10–18.
16. Jackson, R.K., et al., “Initiation and Detonation Characteristics of TATB,” *6th International Symposium on Detonation*, Office of Naval Research Report ACR-221, Coronado, CA, 1976, pp. 755-765.

17. James, H.R., “Links Between Macroscopic Behaviour and Explosive Morphology in Shock to Detonation Transitions," *13th International Detonation Symposium*, Office of Naval Research ONR 351-07-01, Norfolk, VA, 2006, p. 952.
18. Leininger, L., J. Tringe, K. Vandersall, D. Paulsen, M. DeHaven, B. Cracchiola, J. Maienschein, “The Bullet Test for Insentive High Explosive (IHE) Material Qualification: A Demonstration with PBX 9501 and PBX 9502”, LLNL-TR-820591, 2021
19. Mulford, R.N., et al., "Shock Initiation of PBX-9502 at Elevated Temperature." *Shock Compression of Condensed Matter,* AIP Conference Proceedings 370, 1995, p. 855.
20. Parker, G.R., M.D. Homes, E.M. Heatwole, R.M. Broilo, M.M. Pederson, P. Dickson, “Direct Observation of Frictional Ignition in Dropped HMX-based Polymer-bonded Explosives”, Combustion and Flame 221 (2020), pp180–193.
21. Slape, R.J., “Insensitive High Explosive (IHE) Qualification Test Plant”, Mason & Hanger – Silas Mason Co., Inc. Pantex Plant, February 8, 1984.
22. Tarver, C.M., et al., “Manganin Gauge and Reactive Flow Modeling Study of the Shock Initiation of PBX 9501,” *Shock Compression of Condensed Matter*, AIP Conference Proceedings 620, Atlanta, GA, 2001, pp. 1043-1046.
23. Urtiew, P.A., et al., “Shock Sensitivity of IHE at Elevated Temperatures,” *10th International Detonation Symposium*, Office of Naval Research Report ONR 33395-12, Boston, MA, 1993, p. 139.
24. Urtiew, P.A., et al., “Effects of Confinement and Thermal Cycling on the Shock Initiation of LX-17,” *Combustion and Flame* 105, 1996, p. 43.
25. Urtiew, P.A., et al., “Shock Sensitivity of LX-04 at Elevated Temperatures,” *Shock Compression of Condensed Matter*, AIP Conference Proceedings 429, Amherst, MA, 1997, pp. 727-730.
26. Urtiew, P.A., et al., “Shock Initiation of UF-TATB at 250°C,” *Shock Compression of Condensed Matter*, AIP Conference Proceedings 620, Atlanta, GA, 2001, pp.1039-1042.
27. Urtiew, P.A., C.M. Tarver, “Shock Initiation of Energetic Materials at Different Initial Temperatures (Review),” *Combustion, Explosion and Shock Waves* 41, 2005, p. 766.
28. Urtiew, P.A., et al., “Initiation of Heated PBX-9501 Explosive When Exposed to Dynamic Loading,” presented at Zababakhin Scientific Talks, Snezhinsk, Russia, September 5-10, 2005, LLNL report UCRL-CONF-214667, August 17, 2005.
29. Vandersall, K.S., et al., “Low Amplitude Single and Multiple Shock Initiation Experiments and Modeling of LX-04,” *13th International Detonation Symposium*, Norfolk, VA, 2006, pp. 904-913.
30. Vandersall, K.S., et al., “Shock Initiation Experiments on PBX9501 Explosive at 150ºC for Ignition and Growth Modeling,” *Shock Compression of Condensed Matter*, AIP Conference Proceedings 845, Baltimore, MD, 2006, p. 1127.
31. Vandersall, K.S., "LX-10 Summary Sheet," LLNL Explosives Reference Guide, UCRL-WEB-207690, 2006.
32. Vandersall, K.S., et al., “On The Low Pressure Shock Initiation of Octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine Based Plastid Bonded Explosives,” *Journal of Applied Physics* 107, 2010, p. 094906-1.
33. Vandersall, K.S., et al., “Shock Initiation Experiments on the HMX Based Explosive LX-10 with Associated Ignition and Growth Modeling,” *Shock Compression of Condensed Matter*, AIP Conference Proceedings 955, 2007, pp. 1010-1013.

34. Walker, F.E. and R.J. Wasley, “Critical Energy for Shock Initiation of Heterogeneous Explosives,” LLNL Report UCRL-70891 Revision 1, June 7, 1972.

Appendix B DOE memo establishing standard

Department of Energy
National Nuclear Security Administration
P.O. Box 5400
Albuquerque, NM 87185

August 29, 2018

MEMORANDUM FOR DISTRIBUTION

FROM: DANIEL SIGG
DEPUTY ASSOCIATE ADMINISTRATOR FOR SAFETY

SUBJECT: Interim Determination - Approval Processes for Qualification of Insensitive High Explosive Materials and Subassemblies

The Department of Energy (DOE) Environment, Health, Safety, and Security (AU-10) transferred Office of Primary Interest (OPI) responsibilities for DOE-STD-1212-2012, *Explosives Safety*, to the Office of Safety, Infrastructure, and Operations (NA-50).

Current IHE approval requirements in DOE-STD-1212-2012, Chapter IX, paragraph 1.0a, direct a DOE laboratory or operator to submit test data for each explosive through the appropriate Operations Office to the DOE Office of Nuclear and Facility Safety. When NA-50 became the OPI for Explosives Safety, NA-50 assumed this responsibility. NA-50 designated me as the approval authority for the qualification of IHE (Attachment 1, *Explosives Approval Authority Designation for NA-50)*.

Since DOE-STD-1212-2012 does not provide an IHE qualification process for DOE laboratories or operators to follow, the attached IHE Qualification Processes for Materials and Subassemblies should be used until the Explosives Safety Standard is updated to include these processes (Attachment 2, *IHE Qualification Process for Materials and Subassemblies*). These processes were approved by the DOE Explosives Safety Committee.

This interim determination does not affect any previously approved qualifications of IHE material and subassemblies.

If there are any questions please contact Lynn Maestas at (505) 845-6388 or by e-mail at lynn.maestas@nnsa.doe.gov, or Thomas Garcia at (505) 845-5936 or by e-mail at thomas.garcia@nnsa.doe.gov.

cc: w/attachments
- B. Lake, NA-12
- J. Gazda, NA-122
- G. Pugh, NA-122
- L. Maestas, NA-513
- T. Garcia, NA-513
- Records Center

2

Distribution:
R. Lewis, NA-12
Dr. K. Alexander, NA-11
M. Thompson, NA-19
Dr. D. Hauck, NA-191
M. Holecek, KCFO
G. Beausoleil, NPO
N. Nelson-Jean, SRFO
J. Harrell, NA-SN
S. Goodrum, NA-LA
P. Rodrik, LFO
S. Lawrence, NFO
V. Fisher, Office of Secure Transportation
R. Provencher, Idaho National Laboratory
P. Kearns, Argonne National Laboratory

DEPARTMENT OF ENERGY
EXPLOSIVES APPROVAL AUTHORITY DESIGNATION
TO DANIEL SIGG

1. DESIGNATION. As the Associate Administrator for Safety, Infrastructure, and Operations and the leader of the Office of Primary Interest for Department of Energy Technical Standard DOE-STD-1212-2012, I designate Daniel Sigg, the Deputy Associate Administrator for Safety, Office of Safety, Infrastructure, and Operations, as the Approval Authority for insensitive high explosive (IHE) qualifications, as currently described in the Department of Energy Technical Standard DOE-STD-1212-2012, Chapter IX, paragraph 1.0a.

2. RECISSION. The requirement to submit IHE qualifications to DOE Office of Nuclear and Facility Safety is hereby rescinded.

3. LIMITATION.

   3.1. This designation covers all parts of DOE/NNSA requesting an IHE qualification.

   3.2. In exercising the designated authority in this Order, the designee shall receive technical support from the DOE Explosives Safety Committee.

4. AUTHORITY TO REDESIGNATE. This designation may not be redesignated or delegated.

5. DURATION AND EFFECTIVE DATE.

   5.1. All actions taken prior to this designation or pursuant to previous designations are ratified and remain in force as if taken under this designation, unless or until rescinded, amended or superseded.

   5.2. This designation shall expire upon approval of the next revision to DOE-STD-1212.

   5.3. A copy of this designation shall be electronically maintained with other delegations and designations kept by the Office of Safety.

   5.4. This Designation is effective 8/7/2018

James J. McConnell
Associate Administrator
for Safety, Infrastructure, and Operations

Attachment 2 - IHE Qualification Process for Materials and Subassemblies

Processes for qualification of Insensitive High Explosive (IHE) materials and subassemblies listed below must be initiated by the Facility Manager. The Facility Manager (Requestor) initiates this process.

IHE QUALIFICATION PROCESS

1. Requestor performs the appropriate tests in accordance with the requirements of LLNL-TR-679331/LA-UR-15-29238, after coordinating need for material qualification with the appropriate Headquarters (HQs) Program Office (e.g., NA-11, NA-12, or NA-19).
2. The Requestor submits the test data for the candidate explosive to the Explosives Safety Committee (ESC) Chair.
3. The ESC Chair assigns a Task Group for review and recommendation of approval/disapproval of the candidate explosives material.
4. If the request is not recommended for approval, the Task Group documents the rationale and requirements that were not met and provides to the Requestor through the ESC Chair.
5. If the request is recommended for approval, the Task Group assembles the test data and provides to the ESC Chair with recommendation to approve the candidate explosive.
6. The ESC Chair prepares a written recommendation on the approval of the candidate explosive, and submits it along with the supporting explosives package to the Explosives Approval Authority (EAA) Daniel Sigg, Deputy Associate Administrator for Safety.
7. The EAA approves or denies the candidate explosive for qualification as an IHE.
8. Upon finalization of draft Explosives Safety Handbook, the new IHE is added to Table 12-2.

IHE SUBASSEMBLY QUALIFICATION PROCESS

1. The Requestor submits a test plan to the ESC Chair and the test plan will be coordinated with the appropriate DOE/NNSA site, after coordinating need for subassembly qualification with the appropriate Headquarters (HQs) Program Office (e.g., NA-11, NA-12, or NA-19).
2. The ESC Chair assigns a Task Group for review and approval/disapproval of the test plan.
3. The ESC Task Group reviews the test plan for compliance with the IHE subassembly requirements and provides input (if necessary), and approves/denies the test plan.
4. The Requestor submits the test data, for the candidate subassembly, to the ESC Chair.
5. The ESC Chair submits the test data to the Task Group for review and recommendation of approval/disapproval of the candidate subassembly.
6. If the request is not recommended for approval, the Task Group documents the rationale and requirements that were not met and provides to the Requestor through the ESC Chair.
7. If the request is recommended for approval, the Task Group provides the ESC Chair with recommendation to approve the candidate subassembly.
8. The ESC Chair prepares a written recommendation on the approval of the candidate subassembly, and submits it along with the supporting subassembly package to the EAA.

9. The EAA approves or denies the candidate subassembly for qualification as an IHE subassembly.
10. Upon finalization of draft handbook, the new IHE Subassembly is added to Table 12-4.

Appendix C Bill of Materials

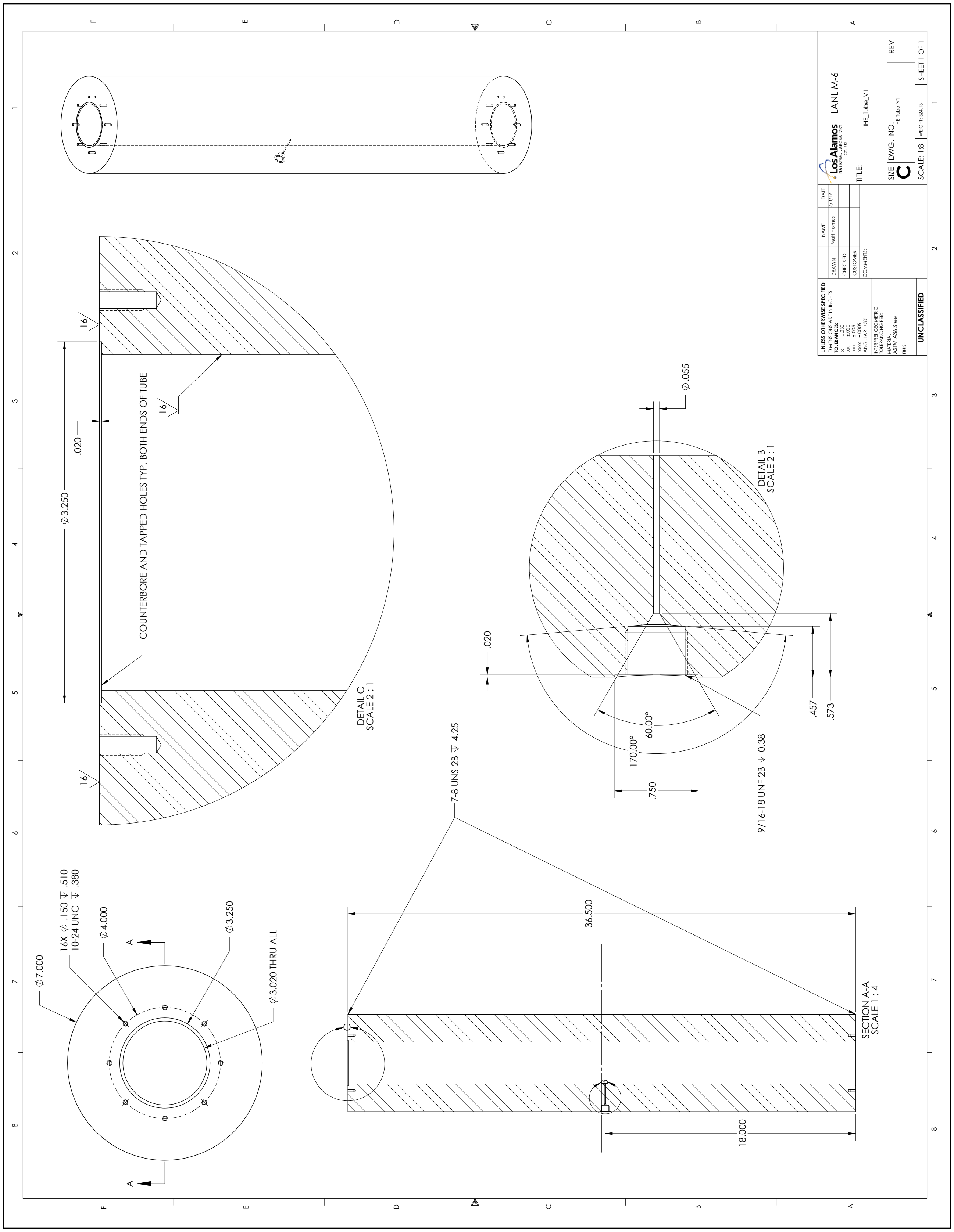
Bill of Materials

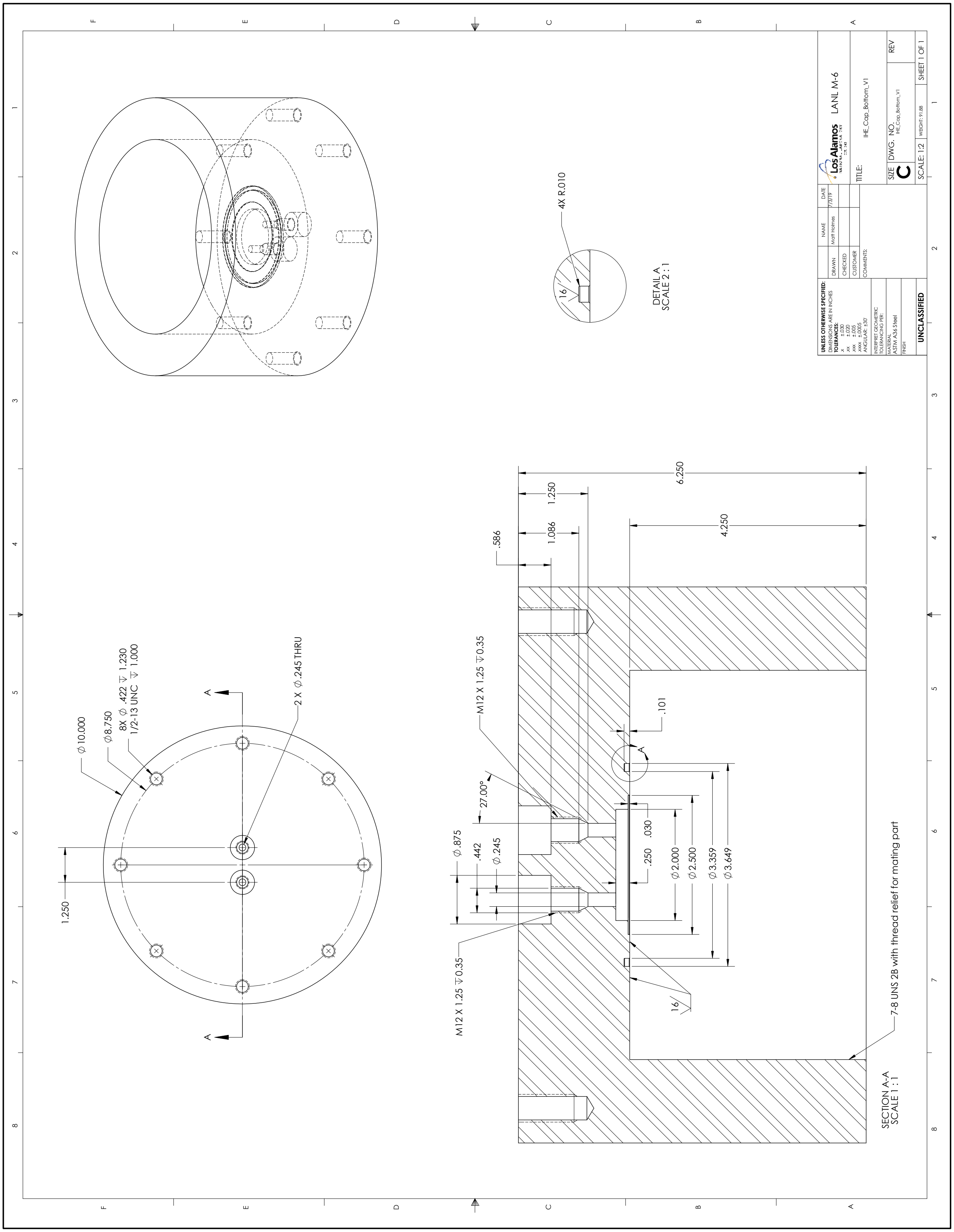
IHE DDT Tube Qualification Test:
Quantity required for Single Test

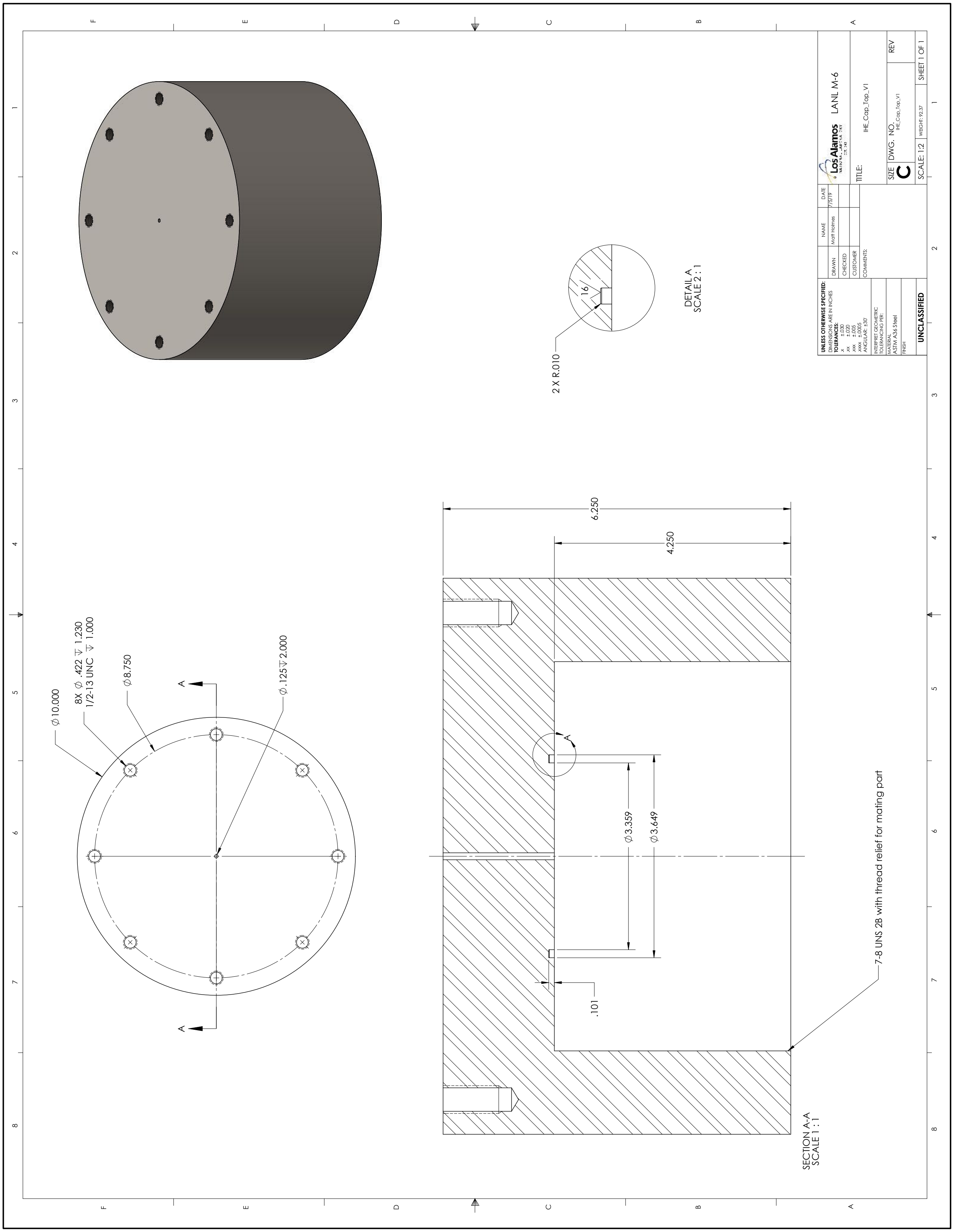
LANL M-6
Matt Holmes 10/27/2020

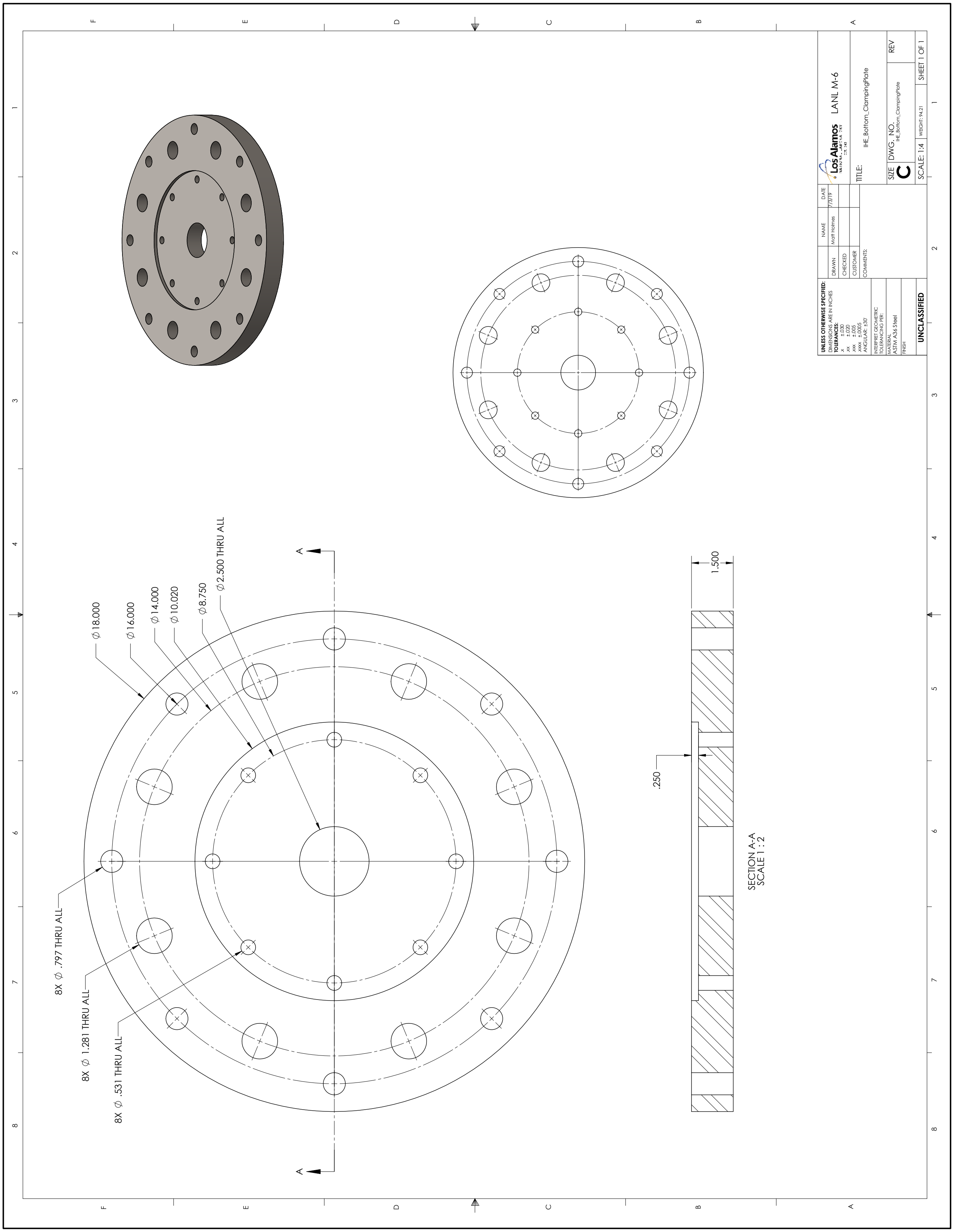
Category	Vendor/ Supplier	Short Description	extra part notes	part # or ID	Quantity	Ordering Info
EXPLOSIVES						
	LANL	3 in. dia. x 3 in. height uniaxially pressed pellet of PBX 9502	for "consolidated material" version		12	in-house
	LANL	loose prills ("molding powder") of PBX 9502	for prills version		5.5 lbs	in-house
MACHINING		*drawing names:*				
	Yeamans Machine Shop	Baseplate_V1		Baseplate	1	refer to quote 10434
	"	Standoff_V1		Standoff	4	refer to quote 10434
	"	IHE_Bottom_ClampingPlate		Clamping Plate	2	refer to quote 10445
	"	IHE_Cap_Bottom_V1	this cap has the two glowplug mounting holes	Igniter End Cap	1	refer to quote 10446
	"	IHE_Cap_Top_V1	this cap has the vent hole	Vent End Cap	1	refer to quote 10434
	"	IHE_Tube_V1		Center Tube	1	refer to quote 10447
VENDOR PURCHASES						
	Mcmaster	3/4-10 x 2.25 hex head bolts	bolting clamps to each other	92620A846	4	reused for all tests
	Mcmaster	3/4-10 x 1.5 hex head bolts	bolting clamps to pivot plates	92620A839	8	reused for all tests
	Mcmaster	3/4-10 nuts		94895A036	12	reused for all tests
	Mcmaster	5/8-11 x 4.5 SHCS	bolting clamps to each other	91251A812	4	reused for all tests
	Mcmaster	5/8-11 nuts		94895A035	4	reused for all tests
	Mcmaster	1/2-13 x 2.25 x 1.25 hex head bolts	screwing clamping plate to igniter cap	91257A721	8	
	Mcmaster	3/4-10 x 2.75 x 1.75 hex bolts	fastening standoffs to clamping plate	91257A844	4	
	Mcmaster	3/4-10 x 1.75 x 1.75 hex bolts	fastening baseplate to standoffs	92620A834	4	
	Mcmaster	o-rings	DASH 237, hard PTFE	9559K221	2	
	Mcmaster	threaded rod 1-1/4-7 x 12ft	cut into 4 ft. long sections. Grade B7 ASTM A193	98957A062	3	
	Mcmaster	1-1/4-7 hex nut	grade 8 steel	94895A859	24	
	Mcmaster	female threaded hex standoffs	M5x0.8 tapped holes both ends, 50 mm long	94868A767	2	
	Mcmaster	M5x0.8 x 10mm SHCS		91290A224	2	
	Mcmaster	M5 lockwashers		91202A230	4	
	Mcmaster	M5 flat washers		98687A110	2	
	Mcmaster	ring terminals	10-12 gauge for #10 screw	8408T33	2	
	Chromalox	main tube heaters	7 in ID, 6 in width, 5000 W each, 40 W/in^2	CB7A6A1P2	4	4 month lead time
	Chromalox	end cap heaters	10 in ID, 3 in width, 2400 W each, 26 W/in^2	CB10A3A1P1	4	4 month lead time
	Omega	internal thermocouples		TJC36-CAXL-020G-12-SMPW-	4	2 month lead time
	Omega	external thermocouples	fiberglass insulation, 6' long, 36 gauge	5SRTC-GG-K-36-72		
	Autoclave Engineers	plugs	these need to be custom drilled per drawing	AP40	1	
	Autoclave Engineers	collar		ACL40	1	
	Bosch	glow plug	Bosch Duraterm Glow Plug	80010/0250201032	2	

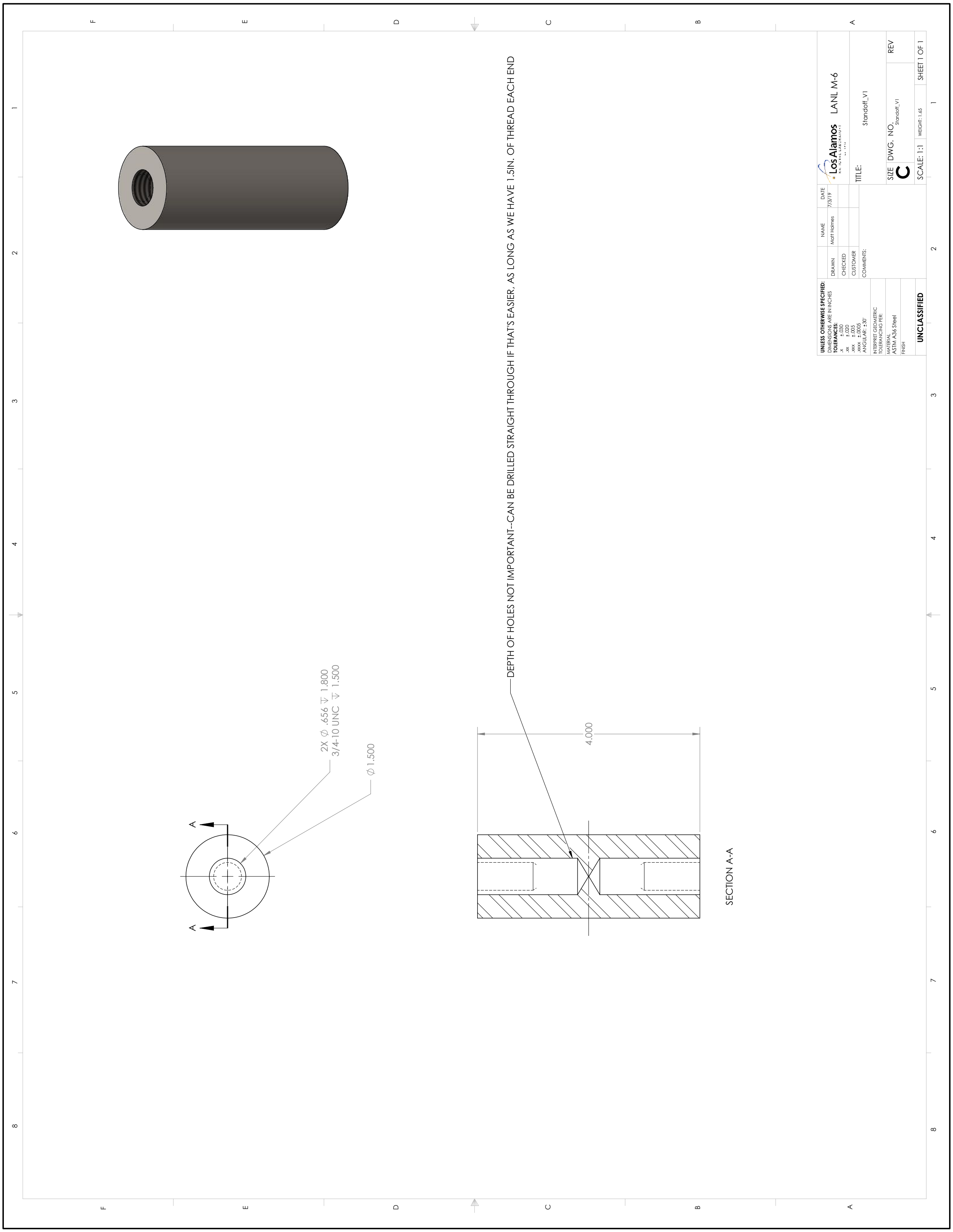
Appendix D Engineering Drawings

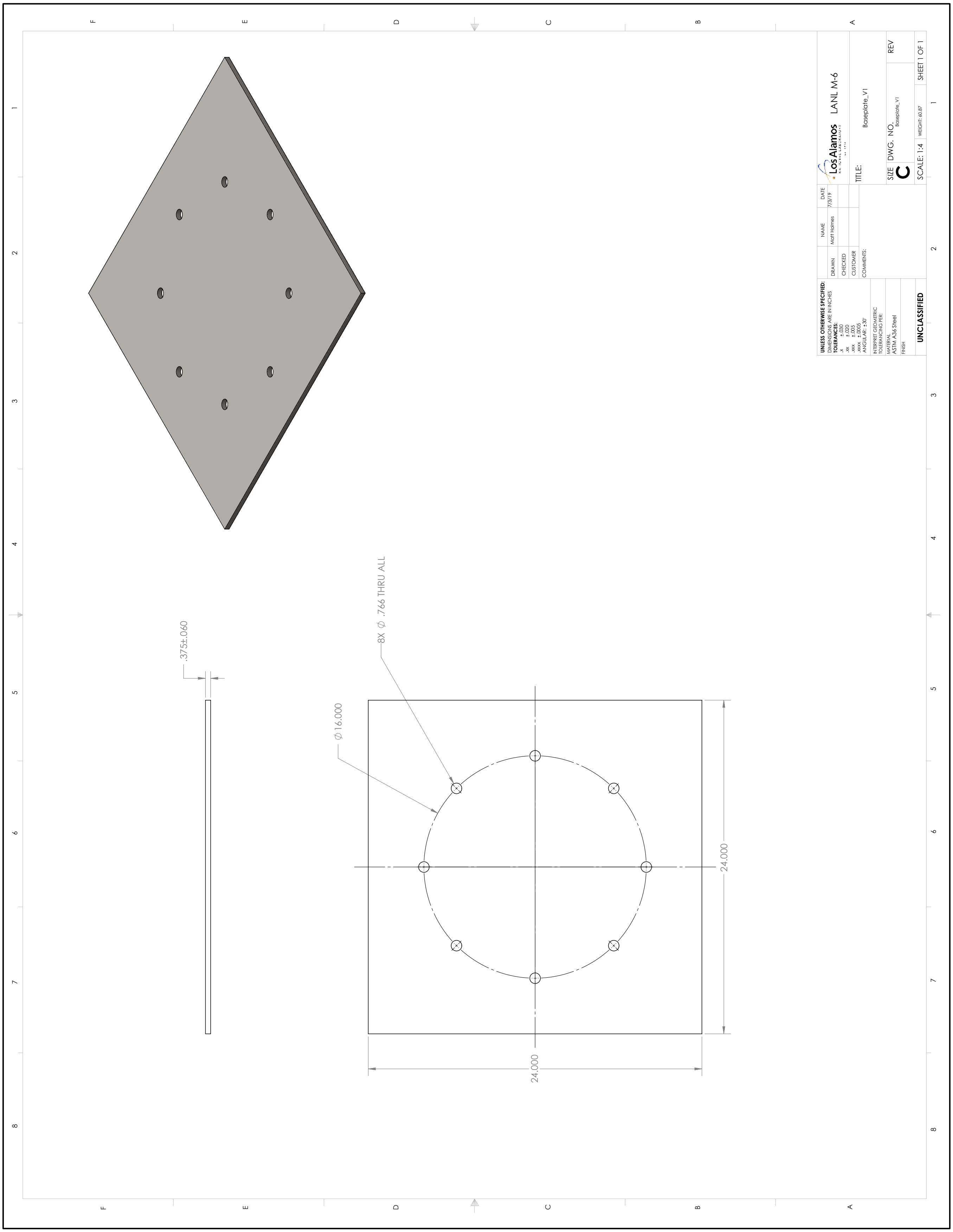


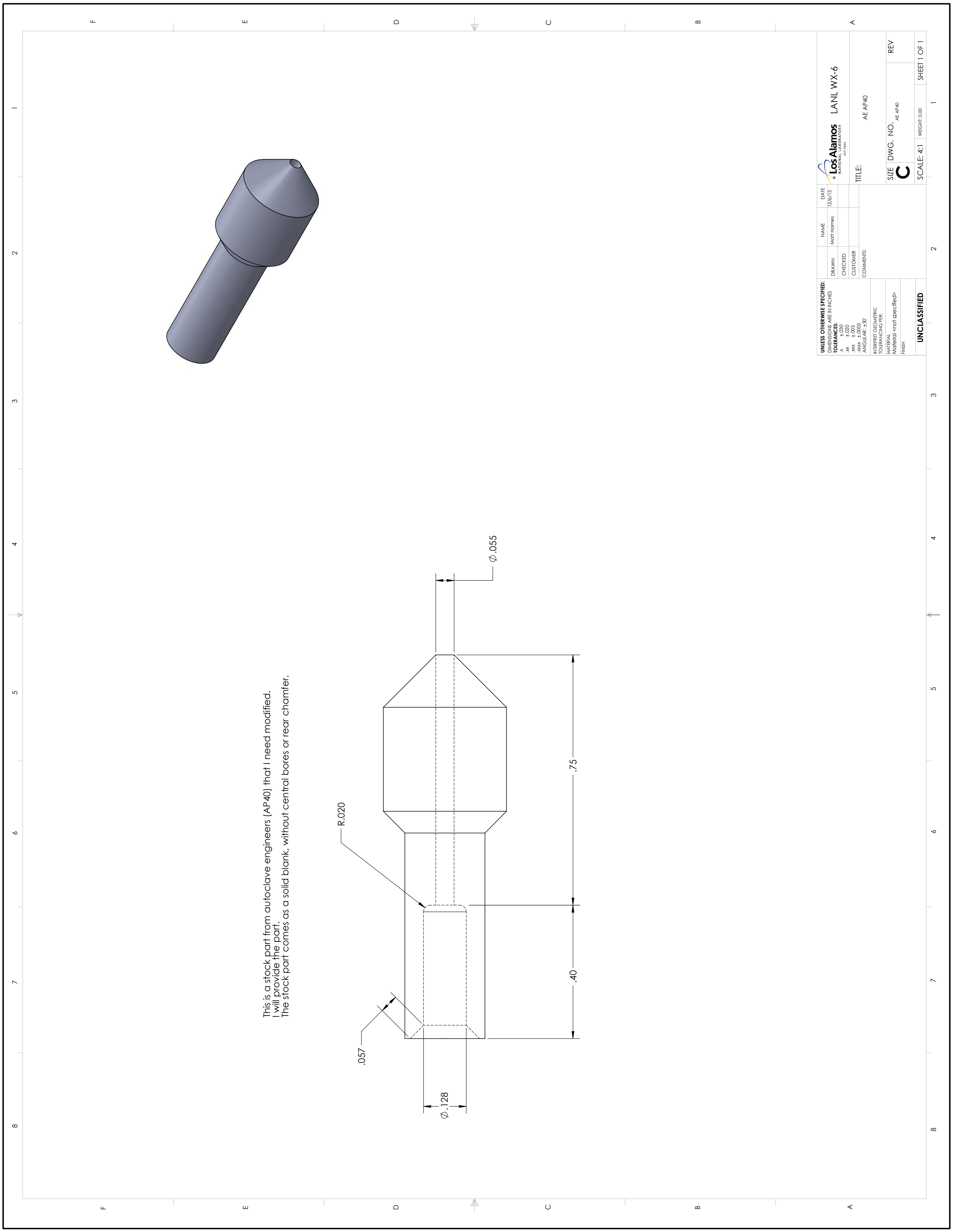

LANL M-6
TITLE: IHE_Cap_Bottom_V1
SIZE C
DWG. NO. IHE_Cap_Bottom_V1
REV
SCALE: 1:2
SHEET 1 OF 1
UNCLASSIFIED
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES
MATERIAL ASTM A36 Steel
DRAWN
CHECKED
CUSTOMER
COMMENTS:
DETAIL A
SCALE 2 : 1
4X R.010
16
SECTION A-A
SCALE 1 : 1
7-8 UNS 2B with thread relief for mating part
M12 X 1.25 ↧ 0.35
M12 X 1.25 ↧ 0.35
2 X ⌀.245 THRU
8X ⌀ .422 ↧ 1.230
1/2-13 UNC ↧ 1.000
⌀10.000
⌀8.750
1.250
6.250
4.250
1.250
1.086
.586
.101
.030
.250
⌀2.000
⌀2.500
⌀3.359
⌀3.649
⌀.875
.442
⌀.245
27.00°
A
A


DETAIL A
SCALE 2 : 1
2 X R.010
16
6.250
4.250
∅3.359
∅3.649
.101
7-8 UNS 2B with thread relief for mating part
SECTION A-A
SCALE 1 : 1
∅10.000
8X ∅ .422 ↧ 1.230
1/2-13 UNC ↧ 1.000
∅8.750
∅.125↧2.000
A
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
DRAWN
Matt Holmes
CHECKED
CUSTOMER
COMMENTS:
MATERIAL
ASTM A36 Steel
FINISH
UNCLASSIFIED
LANL M-6
TITLE:
IHE_Cap_Top_V1
SIZE
C
DWG. NO.
IHE_Cap_Top_V1
REV
SCALE: 1:2
SHEET 1 OF 1


LANL M-6
TITLE:
IHE_Bottom_ClampingPlate
SIZE
C
DWG. NO.
REV
SCALE: 1:4
SHEET 1 OF 1
UNCLASSIFIED
DRAWN
CHECKED
CUSTOMER
COMMENTS:
NAME
DATE
Matt Holmes
MATERIAL
ASTM A36 Steel
FINISH
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
Ø18.000
Ø16.000
Ø14.000
Ø10.020
Ø8.750
Ø2.500 THRU ALL
8X Ø .797 THRU ALL
8X Ø 1.281 THRU ALL
8X Ø .531 THRU ALL
1.500
.250
SECTION A-A
SCALE 1 : 2
A
A


DEPTH OF HOLES NOT IMPORTANT--CAN BE DRILLED STRAIGHT THROUGH IF THAT'S EASIER, AS LONG AS WE HAVE 1.5IN. OF THREAD EACH END
2X ⌀ .656 ↧ 1.800
3/4-10 UNC ↧ 1.500
⌀ 1.500
4.000
SECTION A-A
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
MATERIAL
ASTM A36 Steel
UNCLASSIFIED
DRAWN
Matt Holmes
7/3/19
LANL M-6
TITLE:
Standoff_V1
SIZE
C
DWG. NO.
REV
SCALE: 1:1
SHEET 1 OF 1


.375±.060
8X ⌀ .766 THRU ALL
⌀16.000
24.000
24.000
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
ASTM A36 Steel
FINISH
UNCLASSIFIED
DRAWN Matt Holmes 7/3/19
CHECKED
CUSTOMER
COMMENTS:
Los Alamos
LANL M-6
TITLE:
Baseplate_V1
SIZE C
DWG. NO. Baseplate_V1
REV
SCALE: 1:4
SHEET 1 OF 1


This is a stock part from autoclave engineers (AP40) that I need modified.
I will provide the part.
The stock part comes as a solid blank, without central bores or rear chamfer.
Ø.055
.75
.40
R.020
.057
Ø.128
UNLESS OTHERWISE SPECIFIED:
DRAWN
CHECKED
CUSTOMER
COMMENTS:
NAME
DATE
Matt Holmes
12/6/13
LANL WX-6
TITLE:
AE AP40
SIZE
C
DWG. NO.
REV
SCALE: 4:1
SHEET 1 OF 1
UNCLASSIFIED

Appendix E Machining Quotes

QUOTE

10447

162 East Gate Drive
Los Alamos, NM 87544
(505) 662-9313 phone (505) 662-9806 fax
Email: yms@yeamansmachine.com

To: Matt Holmes
LANL
(505) 665-4107
Fax (505) 667-9809

PO:

YMS will provide the following parts and quantities per specification.

Item	Description	Qty	Unit Cost	Total Cost
1	Tube V1	9	$3,199.00	$28,791.00
			Lot total:	**$28,791.00**

Delivery 12 weeks best effort ARO

Quote Valid for 30 Days

Patrick Yeamans

Thursday, August 1, 2019
Date

10447

QUOTE

10446

162 East Gate Drive
Los Alamos, NM 87544
(505) 662-9313 phone (505) 662-9806 fax
Email: yms@yeamansmachine.com

To: Matt Holmes
LANL
(505) 665-4107
Fax (505) 667-9809

PO:

YMS will provide the following parts and quantities per specification.

Item	Description	Qty	Unit Cost	Total Cost
1	Cap Bottom V1	10	$1,153.00	$11,530.00
			Lot total:	**$11,530.00**

Delivery 12 weeks best effort ARO

Quote Valid for 30 Days

Patrick Yeamans

Thursday, August 1, 2019
Date

10446

QUOTE

10434

162 East Gate Drive
Los Alamos, NM 87544
(505) 662-9313 phone (505) 662-9806 fax
Email: yms@yeamansmachine.com

To: Matt Holmes
LANL
(505) 665-4107
Fax (505) 667-9809

PO:

YMS will provide the following parts and quantities per specification.

Item	Description	Qty	Unit Cost	Total Cost
1	Baseplate V1	9	$472.00	$4,248.00
2	Standoff V1	36	$110.00	$3,960.00
3	Cap Top V1 Certs	9	$1,082.00	$9,738.00
			Lot total:	**$17,946.00**

Delivery 12 weeks best effort ARO

Quote Valid for 30 Days

Patrick Yeamans

Thursday, August 1, 2019
Date

10434

QUOTE

10445

162 East Gate Drive
Los Alamos, NM 87544
(505) 662-9313 phone (505) 662-9806 fax
Email: yms@yeamansmachine.com

To: Matt Holmes
LANL
(505) 665-4107
Fax (505) 667-9809

PO:

YMS will provide the following parts and quantities per specification.

Item	Description	Qty	Unit Cost	Total Cost
1	Bottom Clamping Plate	18	$779.00	$14,022.00
			Lot total:	**$14,022.00**

Delivery 12 weeks best effort

Quote Valid for 30 Days

Patrick Yeamans

Thursday, August 1, 2019
Date

10445

QUOTE

10538

162 East Gate Drive
Los Alamos, NM 87544
(505) 662-9313 phone (505) 662-9806 fax
Email: yms@yeamansmachine.com

To: Matt Holmes
LANL
(505) 665-4107
Fax (505) 667-9809

PO:

YMS will provide the following parts and quantities per specification.

Item	Description	Qty	Unit Cost	Total Cost
1	IHE Tube Stand	1	$11,990.00	$11,990.00
2	Weld/Lot	1	$3,615.00	$3,615.00

Hardware not included **Lot total: $15,605.00**

Delivery Feb 1 best effort

Quote Valid for 30 Days

Patrick Yeamans

Wednesday, December 4, 2019
Date

10538

Appendix F Machining Packing Slip

Yeamans Machine Shop, Inc.

162 Eastgate Drive
Los Alamos, NM 87544
(505) 662-9313 (505) 662-9806 fax

RRB
Packing Slip

Purchase Order/Release ***RRB: 564894***

Ship To: LANL

Preparer:

Requester: Matt Holmes

Qty	*PartName*	*Drawing#:*
9	Baseplate V1	CERT 3366/3367
36	Standoff V1	CERT 3368
18	Bottom Clamping Plate	Certs 3369
10	Cap Bottom V1	Certs 6ea - 3364 4ea - 3365
9	Cap Top V1	Certs 3364
9	Tube V1	Certs 3380

Shipping 1 Lot Complete at $72,289.00

COPY

Received by ____________________ ***Z Number*** __________

Date ________________

Job 10434

Appendix G Steel material certifications

3364

NUCOR
NUCOR STEEL MEMPHIS, INC.

Mill Certification
4/5/2019

MTR #: G1-194524
3601 Paul R Lowry Rd
MEMPHIS, TN 38109
(901) 786-5900
Fax: (901) 786-5901

Sold To: EATON STEEL CORP
10221 CAPITAL AVE
OAK PARK, MI 48237
(248) 398-3434
Fax: (248) 398-1434

Ship To: NICHOLSON TERMINAL & DOCK CO.
380 E. Great Lakes Ave.
RIVER ROUGE, MI 48218
(313) 842-4300

Customer P.O.	170586	Sales Order	172436.1
Product Group	Special Bar Quality	Part Number	30010500R20NSG0
Grade	1018 (S .015-.025)MECH, MACRO, MICRO, GSIZE	Lot #	MM1910026303
Size	10-1/2" (10.5000) Round	Heat #	MM19100263
Product	10-1/2" (10.5000) Round 20' R/L 1018-C2Q3	B.L. Number	G1-356058
Description	1018-C2Q3	Load Number	G1-194524
Customer Spec		Customer Part #	7113

I hereby certify that the material described herein has been manufactured in accordance with the specifications and standards listed above and that it satisfies those requirements.

Roll Date: 3/14/2019 Melt Date: 1/11/2019 Qty Shipped LBS: 38,462 Qty Shipped Bundles: 6

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Al	B
0.19%	0.72%	0.010%	0.021%	0.23%	0.27%	0.09%	0.14%	0.03%	0.005%	0.029%	0.0002%

Sn	Ti	Cb	Ca	Pb	N	H	NICRMO	CEQ
0.006%	0.001%	0.0000%	0.0011%	0.000%	0.0074%	1.3 ppm	0.26%	0.370%

Fe: Balance
NICRMO: Ni+Cr+Mo
CEQ: Standard Carbon Equivalent

Austenitic grain size is equal to 5 or finer by chemical analysis per the latest revision of ASTM A29.

DI value: 0.66

E381 Surface (Back) 1
Oxide Cleanliness: SAE J422 0.0
Brinell Converted Mid-Radius: 150.0bhn
Yield 1: 41.2ksi
Grain Size per ASTM E112 = 6

E381 Mid Radius (Back) 1
Silicate Cleanliness: SAE J422 0.0
Brinell Converted Surface: 150.0bhn
Elongation: 27% in 2"(% in 50.8mm)
Reduction Ratio 3.7 :1

E381 Center (Back) 1
Brinell: 150.000bhn
Tensile 1: 72.7ksi
Reduction of Area: 43%

Steven Gage
Division Metallurgist

Page 1 of 2

NBMG-10 October 1, 2017

3364

NUCOR
NUCOR STEEL MEMPHIS, INC.

Mill Certification
4/5/2019

MTR #: G1-194524
3601 Paul R Lowry Rd
MEMPHIS, TN 38109
(901) 786-5900
Fax: (901) 786-5901

Sold To: EATON STEEL CORP
10221 CAPITAL AVE
OAK PARK, MI 48237
(248) 398-3434
Fax: (248) 398-1434

Ship To: NICHOLSON TERMINAL & DOCK CO.
380 E. Great Lakes Ave.
RIVER ROUGE, MI 48218
(313) 842-4300

Customer P.O.	170586	Sales Order	172436.1
Product Group	Special Bar Quality	Part Number	30010500R20NSG0
Grade	1018 (S .015-.025)MECH, MACRO, MICRO, GSIZE	Lot #	MM1910026303
Size	10-1/2" (10.5000) Round	Heat #	MM19100263
Product	10-1/2" (10.5000) Round 20' R/L 1018-C2Q3	B.L. Number	G1-356058
Description	1018-C2Q3	Load Number	G1-194524
Customer Spec		Customer Part #	7113

I hereby certify that the material described herein has been manufactured in accordance with the specifications and standards listed above and that it satisfies those requirements.

ASTM E381
Surface: 1 Mid Radius: 1 Center: 1

ASTM E45 Method A (Worst)
Sulfides: T: 2.0 H: 1.5 Alumina: T: 0.0 H: 0.0 Silicates: T: 0.0 H: 0.0 Globular: T: 1.0 H: 0.5

Specification Comments: EAF, LMF, VACUUM DEGASSED, CONTINUOUSLY CAST ASTM A29/A29M-16 ASTM A576-17

1. All manufacturing processes, including melting have been performed in the U.S.A.
2. No mercury, mercury compounds or mercury containing devices came into contact with this product.
3. Welding or weld repair was not perfomed on this material.
4. This material conforms to the specifications described on this document. This document may not be reproduced except in full, without written approval of Nucor Corporation.
5. This product is NAFTA certified under Paragraph "B" of the NAFTA rule of origin.
6. Material verified not to exceed background radiation levels.
7. This document is in compliance with EN 10204 "type 3.1"
8. The following tests are outside the ISO 17025 Laboratory Scope for Nucor Steel Memphis: Hydrogen, Brinell, and Non-Destructive Testing
9. Results reported for ASTM E45 (inclusion content) and ASTM E112 (Grain size) are provided as interpretation of ASTM procedures.
10. Test procedures are performed in compliance with the following ASTM standards: Chemical Analysis: E415/E1019, Grain Size: E112, Macroetch: E381, Tensile and Hardness Testing: A370/E8, Charpy Impact: E23, Decarburization Depth: 1077, Microcleanliness: E45.
11. ASTM E23 tests conducted with 8mm striker radius upon 10mm x 10mm V notch specimen.
12. Export Country: USA email Memphis.Sales@nsmem.nucor.com

Steven Gage
Division Metallurgist

Page 2 of 2

NBMG-10 October 1, 2017

3364

Material Certification Report 440720

Issued By	NUCOR STEEL-MEMPHIS
Batch No.	Heat MM19100263

Chemistry	Description	Value	Units
C	Carbon	0.19000	PWGT
Mn	Manganese	0.72000	PWGT
P	Phosphorus	0.01000	PWGT
S	Sulfur	0.02100	PWGT
Si	Silicon	0.23000	PWGT
Ni	Nickel	0.09000	PWGT
Cr	Chromium	0.14000	PWGT
Mo	Molybdenum	0.03000	PWGT
Al	Aluminum	0.02900	PWGT
Cu	Copper	0.27000	PWGT
V	Vanadium	0.00500	PWGT
Cb	Columbium	0.00000	PWGT
N	Nitrogen	0.00740	PWGT
Geometry	**Description**	**Value**	**Units**
DIAMETER	Diameter	10.5000	IN
Cleanliness	**Description**	**Value**	**Units**
SAE J422 OX	SAE J422 Oxide Rating	0.0	NUM
SAE J422 SI	SAE J422 Silicate Rating	0.0	NUM
MACRO ETCH	Report macro etch results.	Satisfactory	.
Structure	**Description**	**Value**	**Units**
RPT GRAIN SIZE	Reported Grain Size	Fine Grain	.
ASTM Standard	**Description**	**Value**	**Units**
A576-95	Steel Bars, Carbon, Hot Roll SBQ	CONFORMS	.
Mill Processing	**Description**	**Value**	**Units**
MELT COUNTRY	Melted in Country	USA	.
ROLLED COUNTRY	Rolled in Country	USA	.
RED RATIO	Reduction Ratio	1.70	RED

We hereby certify the above to be a true copy of data represented in company records. This steel was not subject to weld repair or exposed to mercury while in the possession of Eaton Steel.

Created on 08 APRIL 2019
Marc Benjamin, Corporate Metallurgist

Eaton Steel Bar Company

3364

Eaton Steel Bar Company Inspection Certificate 1795950 — EN 10204:2004-3.1

Customer	BOL	Ship Date	Customer PO	Item	Customer Item	Item Description
RYERSON CORP	248072	14-May-2019	4500941320	7113 rev 002	160000147	10-1/2 HR RD 1018 16/20ft SBQ FG

All bundles listed below were produced using steel from Heat MM19100263 issued by NUCOR STEEL-MEMPHIS and were completed from Eaton Steel Job NO JOB.

Chemistry	Description	Value	Units
C	Carbon	0.19000	PWGT
Mn	Manganese	0.72000	PWGT
P	Phosphorus	0.01000	PWGT
S	Sulfur	0.02100	PWGT
Si	Silicon	0.23000	PWGT
Ni	Nickel	0.09000	PWGT
Cr	Chromium	0.14000	PWGT
Mo	Molybdenum	0.03000	PWGT
Al	Aluminum	0.02900	PWGT
Cu	Copper	0.27000	PWGT
V	Vanadium	0.00500	PWGT
Cb	Columbium	0.00000	PWGT
N	Nitrogen	0.00740	PWGT
Cleanliness	**Description**	**Value**	**Units**
SAE J422 OX	SAE J422 Oxide Rating	0.0 - 5.0	NUM
SAE J422 SI	SAE J422 Silicate Rating	0.0 - 5.0	NUM
MACRO ETCH	Report macro etch results.		.
Geometry	**Description**	**Value**	**Units**
DIAMETER	Diameter	10.5000 - 10.7500	IN
Mill Processing	**Description**	**Value**	**Units**
MELT COUNTRY	Melted in Country	USA	.
ROLLED COUNTRY	Rolled in Country	USA	.
RED RATIO	Reduction Ratio	3.70	RED
ASTM Standard	**Description**	**Value**	**Units**
A576-95	Steel Bars, Carbon, Hot Roll SBQ	CONFORMS	.
Structure	**Description**	**Value**	**Units**
RPT GRAIN SIZE	Reported Grain Size	Fine Grain	.

Tag Number	Qty	Units	Length
022-2484149	6625	LBS	21ft9in

Bundle tags with Eaton Steel identifiers reference the steel grade, heat, purchase order number where applicable, part number, product description and quantity. Material produced in accordance with Eaton Steel's Quality Manual QM-00002 Rev 2 dated 10/15/2018.

We hereby certify the above to be in conformance, and a true copy of data represented in company records. This steel was not subject to weld repair or exposed to mercury while in the possession of Eaton Steel.

Created on 14-May-2019
Marc Benjamin, Corporate Metallurgist

This document was prepared by means of electronic data processing and is valid without signature.

10221 Capital Avenue, Oak Park, MI 48237 USA
http://www.eatonsteel.com
Tel: 248-398-3434
Fax: 248-398-1434

3364

RYERSON

Page 1/ 1

6600 Highway 85
COMMERCE CITY, CO 80022-2394

CERTIFICATION OF MATERIAL

CUSTOMER: YEAMAN'S MACHINE SHOP
162 EAST GATE DRIVE
LOS ALAMOS, LOS ALAMOS
NM 87544-3304

SALES ORDER NUMBER: 15366072 000020
CUSTOMER PURCHASE ORDER: 10434 20
CUSTOMER PART NUMBER:
DELIVERY NUMBER: 804425684 000010

MATERIAL NUMBER: 170001396
INVENTORY DESCRIPTION: RD HR 1018 10.5 SHORT

FINISHED ITEM DESCRIPTION: CARB Bar RD HR 1018
10.5in X 7in

HEAT NUMBER(s)	SLAB/COIL/TEST NUMBER (if applicable)
MM19100263	N/A
W1917	022-2434213

CERTIFICATION

A survey of our material sources has indicated that neither mercury nor radioactive substances is introduced into their products, or is used in any of their processes. While we make no independent tests for mercury or radiation, there is nothing in Ryerson's system which could be expected to introduce contamination of either type.

This document certifies that the material described above was shipped in accordance with your order. The producer of the material has certified to Ryerson that it was produced in accordance with the following spec:

ASTM A576

09/13/2019

Thomas Endres
Thomas Endres
Vice President - Procurement

3365

Page 1/ 1

RYERSON

6600 Highway 85
COMMERCE CITY, CO 80022-2394

CERTIFICATION OF MATERIAL

CUSTOMER: YEAMAN'S MACHINE SHOP
162 EAST GATE DRIVE
LOS ALAMOS, LOS ALAMOS
NM 87544-3304

SALES ORDER NUMBER: 15366072 000020
CUSTOMER PURCHASE ORDER: 10434 20
CUSTOMER PART NUMBER:
DELIVERY NUMBER: 804425684 000010

MATERIAL NUMBER: 170001396
INVENTORY DESCRIPTION: RD HR 1018 10.5 SHORT

FINISHED ITEM DESCRIPTION: CARB Bar RD HR 1018
10.5in X 7in

HEAT NUMBER(s)	SLAB/COIL/TEST NUMBER (if applicable)
MM19100263	N/A
W1917	022-2434213

CERTIFICATION

A survey of our material sources has indicated that neither mercury nor radioactive substances is introduced into their products, or is used in any of
their processes. While we make no independent tests for mercury or radiation, there is nothing in Ryerson's system which could be expected to
introduce contamination of either type.

This document certifies that the material described above was shipped in accordance with your order. The producer of the material has certified to
Ryerson that it was produced in accordance with the following spec:

ASTM A576

09/11/2019

Thomas Endres
Thomas Endres
Vice President · Procurement

3365

Steel Certificate of Test

1835 Dueber Ave. S.W.
Canton, Ohio 44706
ID #0476190-1

TIMKENSTEEL

Page 1 of 2

8/06/2018

SOLD TO
Eaton Steel Corporation
10221 Capital
OAK PARK, MI 48237 USA

SHIP TO
LATER
LATER
DOMESTIC

Customer Order: 167362 7113 TBD   Customer Part Number: 7113
Mill Order: 20105-C (2140168)   Heat Number(s): W1917

Description of Material

DIAMETER: 10.500 in (266.700 mm)
Shape: RD
Prod Type: BAR
Sales Type: 1018
Int Quality: COMMERCIAL
Condition: HOT ROLL

Specification

- EATON STEEL 7113 Rev. 2 12/19/2002 EXCEPT ACTUAL NON-METS, EXCEPT ACTUAL MACROETCH
- ASTM A 576/A 576M Rev. 17 11/01/2017 EXCEPT AS NOTED

Chemistry Information

	%C	%Mn	%P	%S	%Si	%Cr	%Ni	%Mo	%Cu	%Al	%V	%Cb	%N
SPEC Ladle Min:	.15	.60			.15								
SPEC Ladle Max:	.20	.90	.030	.050	.35	.25	.25	.06	.35				
W1917 Ladle:	.18	.81	.013	.012	.27	.11	.07	.02	.18	.034	.002	.001	.0062

Testing of elements performed at TimkenSteel Chemistry Labs except where noted.

Metallurgy Information

SPEC: Chemistry (Info Only)
Heat W1917 DI Caterpillar: 0.62
SPEC: Grain Size SIZE FINE
FINE
SPEC: MacroEtch Std SURFACE 2 Max RANDOM 2 Max CENTER 2 Max
MACROETCH RATINGS EQUAL TO OR BETTER THAN STATED REQUIREMENTS BASED ON PERIODIC TESTING.
SPEC: NonMet SO S 5 Max O 5 Max
SO TYPE NONMETALLIC INCLUSION RATINGS EQUAL TO OR BETTER THAN STATED REQUIREMENTS BASED ON PERIODIC TESTING.
All Hardness and Tensile testing performed at TimkenSteel Metallurgical Lab except where noted.

Heat W1917 Melt Source: USA
Manufacturing: USA
Bottom Pour Ingot Cast Process
REDUCTION RATIO - 9.1:1

When shipping document is attached it becomes part of this certification.

We certify the above materials have been inspected and tested in accordance with the methods prescribed in the governing specifications and consistent with our Standard Commercial Terms and Conditions for Sale, Manufacture, and Shipping, which are incorporated into and made part of this certification. The results of such inspections and tests conform with the applicable requirements including the purchase order, specification(s) and exception(s). This certificate or report shall not be reproduced except in full, without the written approval of TimkenSteel Corporation.

Notarized:______________________ by Vinicius Silva
NOTARY PUBLIC
Vinicius Silva, METALLOGRAPHER

TimkenSteel Corporation

3365

Steel Certificate of Test

1835 Dueber Ave. S.W.
Canton, Ohio 44706
ID #0476190-1

Page 2 of 2

TIMKENSTEEL

8/06/2018

Customer Order: 167362 7113 TBD
Mill Order: 20105-C (2140168)
Customer Part Number: 7113
Heat Number(s): W1917

Material melted and produced in the USA

TimkenSteel certifies that there is no mercury or radio-active material used in the melting or processing.

No welding of this material has occurred.

Material melted via electric furnace.

In reference to Section 1502 ("Conflict Minerals") of the Dodd-Frank Wall Street Reform and Consumer Protection Act, no tantalum, tin, tungsten or gold was intentionally added to this material.

TimkenSteel Corporation

3365

Material Certification Report 432884

Issued By	TIMKEN-CANTON
Batch No.	Heat W1917

Chemistry	Description	Value	Units
C	Carbon	0.18000	PWGT
Mn	Manganese	0.81000	PWGT
P	Phosphorus	0.01300	PWGT
S	Sulfur	0.01200	PWGT
Si	Silicon	0.27000	PWGT
Ni	Nickel	0.07000	PWGT
Cr	Chromium	0.11000	PWGT
Mo	Molybdenum	0.02000	PWGT
Al	Aluminum	0.03400	PWGT
Cu	Copper	0.18000	PWGT
V	Vanadium	0.00200	PWGT
Cb	Columbium	0.00100	PWGT
N	Nitrogen	0.00620	PWGT
Geometry	**Description**	**Value**	**Units**
DIAMETER	Diameter	10.5000	IN
Cleanliness	**Description**	**Value**	**Units**
SAE J422 OX	SAE J422 Oxide Rating	5.0	NUM
SAE J422 SI	SAE J422 Silicate Rating	5.0	NUM
MACRO ETCH	Report macro etch results.	Satisfactory	-
Structure	**Description**	**Value**	**Units**
RPT GRAIN SIZE	Reported Grain Size	Fine Grain	-
ASTM Standard	**Description**	**Value**	**Units**
A576-95	Steel Bars, Carbon, Hot Roll SBQ	CONFORMS	-
Mill Processing	**Description**	**Value**	**Units**
MELT COUNTRY	Melted in Country	USA	-
ROLLED COUNTRY	Rolled in Country	USA	-
RED RATIO	Reduction Ratio	9.10	RED

We hereby certify the above to be a true copy of data represented in company records. This steel was not subject to weld repair or exposed to mercury while in the possession of Eaton Steel.

Created on 07 AUGUST 2018
Marc Benjamin, Corporate Metallurgist

Eaton Steel Bar Company

3365

Eaton Steel Bar Company Inspection Certificate 1776437 — EN 10204:2004-3.1

Customer	BOL	Ship Date	Customer PO	Item	Customer Item	Item Description
RYERSON CORP	243601	11-Feb-2019	4500929975	7113 rev 002	160000147	10-1/2 HR RD 1018 16/20ft SBQ FG

All bundles listed below were produced using steel from Heat W1917 issued by TIMKEN-CANTON and were completed from Eaton Steel Job NO JOB.

Chemistry	Description	Value	Units
C	Carbon	0.18000	PWGT
Mn	Manganese	0.81000	PWGT
P	Phosphorus	0.01300	PWGT
S	Sulfur	0.01200	PWGT
Si	Silicon	0.27000	PWGT
Ni	Nickel	0.07000	PWGT
Cr	Chromium	0.11000	PWGT
Mo	Molybdenum	0.02000	PWGT
Al	Aluminum	0.03400	PWGT
Cu	Copper	0.18000	PWGT
V	Vanadium	0.00200	PWGT
Cb	Columbium	0.00100	PWGT
N	Nitrogen	0.00620	PWGT
Cleanliness	**Description**	**Value**	**Units**
SAE J422 OX	SAE J422 Oxide Rating	0.0 - 5.0	NUM
SAE J422 SI	SAE J422 Silicate Rating	0.0 - 5.0	NUM
MACRO ETCH	Report macro etch results.		.
Geometry	**Description**	**Value**	**Units**
DIAMETER	Diameter	10.5000 - 10.7500	IN
Mill Processing	**Description**	**Value**	**Units**
MELT COUNTRY	Melted in Country	USA	.
ROLLED COUNTRY	Rolled in Country	USA	.
RED RATIO	Reduction Ratio	9.10	RED
ASTM Standard	**Description**	**Value**	**Units**
A576-95	Steel Bars, Carbon, Hot Roll SBQ	CONFORMS	.
Structure	**Description**	**Value**	**Units**
RPT GRAIN SIZE	Reported Grain Size	Fine Grain	.

Tag Number	Qty	Units	Length
022-2434213	6063	LBS	16ft/20ft

Bundle tags with Eaton Steel identifiers reference the steel grade, heat, purchase order number where applicable, part number, product description and quantity. Material produced in accordance with Eaton Steel's Quality Manual QM-00002 Rev 0 dated 11/21/2013.

We hereby certify the above to be in conformance, and a true copy of data represented in company records. This steel was not subject to weld repair or exposed to mercury while in the possession of Eaton Steel.

Created on 11-Feb-2019
Marc Benjamin, Corporate Metallurgist
[illegible]

10221 Capital Avenue, Oak Park, MI 48237 USA
http://www.eatonsteel.com
Tel: 248-398-3434
Fax: 248-398-1434

SSAB

1770 Bill Sharp Boulevard, Muscatine, IA 52761-9412, US

Test Certificate

⚠ **WARNING:** This product can expose you to chemicals including nickel and nickel compounds, which are known to the State of California to cause cancer. For more information go to www.P65Warnings.ca.gov.

Form TC1: Revision 4: Date 6 Feb 2019

Customer:
JOSEPH T. RYERSON & SON, INC.
ACCOUNTS PAYABLE DEPT.
PO BOX 91601
LUBBOCK
TX 79490-1601

Customer P.O.No.: 4500921741 | **Mill Order No.** 41-561158-01 | **Shipping Manifest:** MR370827

Product Description: ASTM A36(14)/A709(18)36/ASME SA36(17)
AASHTO M270(15)36

Ship Date: 15 Mar 19 | **Cert No:** 061762171
Cert Date: 15 Mar19 | (Page 1 of 1)

Size: 1.750 X 96.00 X 240.0 (IN)

Tested Pieces:				Tensiles:							Charpy Impact Tests												
Heat Id	Piece Id	Piece Dimensions	Tst Loc	YS (KSI)	UTS (KSI)	%RA	Elong % 2in	Elong % 8in	Tst Dir	Hardness	Abs. Energy(FTLB) 1	2	3	Avg	% Shear 1	2	3	Avg	Tst Tmp	Tst Dir	Tst Siz (mm)	BDWTT Tmp	%Shr
B9B574	E17	1.756 (DISCRT)	L	50	75			27	T														

Chemical Analysis

Heat Id	C	Mn	P	S	Si	Tot Al	Cu	Ni	Cr	Mo	Cb	V	Ti	B	N	ORGN
B9B574	.19	1.04	.012	.001	.25	.028	.30	.15	.14	.04	.001	.001	.008	.0005	.0057	USA

KILLED STEEL
MERCURY IS NOT A METALLURGICAL COMPONENT OF THE STEEL AND NO MERCURY WAS INTENTIONALLY ADDED DURING THE MANUFACTURE OF THIS PRODUCT.
! WARNING: THIS PRODUCT CAN EXPOSE YOU TO CHEMICALS INCLUDING NICKEL AND NICKEL COMPOUNDS, WHICH ARE KNOWN TO THE STATE OF CALIFORNIA TO CAUSE CANCER.
FOR MORE INFORMATION GO TO WWW.P65WARNINGS.CA.GOV.
MTR EN 10204:2004 INSPECTION CERTIFICATE 3.1 COMPLIANT
100% MELTED AND MANUFACTURED IN THE USA.
PRODUCTS SHIPPED:
B9B574 E17 PCES: 2, LBS: 22870

(P) Cust Part #: 160005011

WE HEREBY CERTIFY THAT THIS MATERIAL WAS TESTED IN ACCORDANCE WITH, AND MEETS THE REQUIREMENTS OF, THE APPROPRIATE SPECIFICATION

Brian Wales
SENIOR METALLURGIST - PRODUCT

3369

3369

RYERSON

Page 1/ 1

6600 Highway 85
COMMERCE CITY, CO 80022-2394

CERTIFICATION OF MATERIAL

CUSTOMER: YEAMAN'S MACHINE SHOP
162 EAST GATE DRIVE
LOS ALAMOS, LOS ALAMOS
NM 87544-3304

SALES ORDER NUMBER: 15366072 000050
CUSTOMER PURCHASE ORDER: 10434 50
CUSTOMER PART NUMBER:
DELIVERY NUMBER: 804425684 000040

MATERIAL NUMBER: 170003488
INVENTORY DESCRIPTION: PLT A36 1.75 SHORT

FINISHED ITEM DESCRIPTION: CARB PLT A36
CIRCLE 1.75in X 18.25in OD

HEAT NUMBER(s)	SLAB/COIL/TEST NUMBER (if applicable)
B9B574	3801420

CERTIFICATION

A survey of our material sources has indicated that neither mercury nor radioactive substances is introduced into their products, or is used in any of
their processes. While we make no independent tests for mercury or radiation, there is nothing in Ryerson's system which could be expected to
introduce contamination of either type.

This document certifies that the material described above was shipped in accordance with your order. The producer of the material has certified to
Ryerson that it was produced in accordance with the following spec:
ASTM A36

09/11/2019

Thomas Endres

Thomas Endres
Vice President - Procurement

3380

RT09741199

NUCOR
NUCOR STEEL MEMPHIS, INC.

Mill Certification
5/24/2019

MTR #: G1-196935
3601 Paul R Lowry Rd
MEMPHIS, TN 38109
(901) 786-5900
Fax: (901) 786-5901

Sold To: ALRO STEEL CORP
PO BOX 927
JACKSON, MI 49204-0927
(517) 787-5500

Ship To: ALRO MILWAUKEE
3000 N 114TH ST
WAUWATOSA, WI 53222-4209

Customer P.O.	MW14149223	Sales Order	175802.1
Product Group	Special Bar Quality	Part Number	30007250R20NSG0
Grade	1018 (S .015-.025)MECH, MACRO, MICRO, GSIZE	Lot #	MM1810487502
Size	7-1/4" (7.2500) Round	Heat #	MM18104875
Product	7-1/4" (7.2500) Round 20' R/L 1018-C2Q3	B.L. Number	G1-359331
Description	1018-C2Q3	Load Number	G1-196935
Customer Spec		Customer Part #	06248000

I hereby certify that the material described herein has been manufactured in accordance with the specifications and standards listed above and that it satisfies those requirements.

Roll Date: 8/8/2018 Melt Date: 6/23/2018 Qty Shipped LBS: 8,505 Qty Shipped Bundles: 3

16-22 ft random
20000# max bundle
Rec Hrs 7am 2 pm mon-fri
call for appt 414-453-1700

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Al	B
0.18%	0.74%	0.008%	0.025%	0.22%	0.26%	0.11%	0.14%	0.05%	0.004%	0.027%	0.0002%
Sn	Ti	Cb	Ca	Pb	N	H	NICRMO	CEQ			
0.006%	0.002%	0.0039%	0.0011%	0.000%	0.0052%	1.8 ppm	0.30%	0.370%			

Fe: Balance
NICRMO: Ni+Cr+Mo
CEQ: Standard Carbon Equivalent

Austenitic grain size is equal to 5 or finer by chemical analysis per the latest revision of ASTM A29.

DI value: 0.68

E381 Surface (Back) 1	E381 Mid Radius (Back) 1	E381 Center (Back) 1
Brinell: 134.000bhn	Brinell Converted Mid-Radius: 137.0bhn	Brinell Converted Surface: 134.0bhn
Tensile 1: 71.0ksi	Yield 1: 41.6ksi	Elongation: 31% in 2"(% in 50.8mm)
Reduction of Area: 46%	Grain Size per ASTM E112 = 6	Reduction Ratio 7.7 :1

Steven Gage
Division Metallurgist

NBMG-10 October 1, 2017

Page 1 of 1

3380

RT09741199

NUCOR

NUCOR STEEL MEMPHIS, INC.

Mill Certification
5/24/2019

MTR #: G1-196935
3601 Paul R Lowry Rd
MEMPHIS, TN 38109
(901) 786-5900
Fax: (901) 786-5901

Sold To: ALRO STEEL CORP
PO BOX 927
JACKSON, MI 49204-0927
(517) 787-5500

Ship To: ALRO MILWAUKEE
3000 N 114TH ST
WAUWATOSA, WI 53222-4209

Customer P.O.	MW14149223	Sales Order	175802.1
Product Group	Special Bar Quality	Part Number	30007250R20NSG0
Grade	1018 (S .015-.025)MECH, MACRO, MICRO, GSIZE	Lot #	MM1810487502
Size	7-1/4" (7.2500) Round	Heat #	MM18104875
Product	7-1/4" (7.2500) Round 20' R/L 1018-C2Q3	B.L. Number	G1-359331
Description	1018-C2Q3	Load Number	G1-196935
Customer Spec		Customer Part #	08248000

I hereby certify that the material described herein has been manufactured in accordance with the specifications and standards listed above and that it satisfies those requirements.

ASTM E381
Surface: 1 Mid Radius: 1 Center: 1

ASTM E45 Method A (Worst)
Sulfides: T: 1.5 H: 2.0 Alumina: T: 0.0 H: 0.0 Silicates: T: 0.0 H: 0.0 Globular: T: 1.0 H: 0.5

Specification Comments: EAF, LMF, VACUUM DEGASSED, CONTINUOUSLY CAST CAT 1E0065 REV 56 UP TO 8"RD JDM A0 QL 2 LATEST REV UP TO 9"RD ASTM A576-90B LATEST HOT ROLLED ASTM A36 HR1018

Steven Gage
Division Metallurgist

NBMG-10 October 1, 2017

Page 2 of 1

Appendix H Assembly Procedure

Assembly Procedure
IHE qualification DDT tube cookoff experiments

EXPERIMENT RECORD
Starting Date: ____
Experiment ID: ___________________________________
Assembly team: _______________________________________

NOTES

1. Use figures for component identification. Component names are boldfaced.
2. Components are palletized when received from machine shop. Tube sections are oriented horizontally on the pallet.
3. Various options exist for the assembly location, if/when the assembly is moved. For the purposes of this procedure, we will be assembling on the skid test pad and the firing mound. Once the assembly work on the skid pad is completed; additional assembly work is continued just outside a pre-built block house on a hard work surface. The unit is mostly assembled outside the block house on the assembly stand, and is then rolled into the block house and placed free-standing on the ground. For remaining assembly. The block house is built with sufficient interior room for worker access in order to perform the final assembly steps.
4. Print separate hardcopy of this assembly procedure for each experiment. Check off steps as they are completed and note deviations, difficulties, or modifications to the procedure.

Basic Tool List (additional items may be necessary)
15/16 wrench or socket
2 ea. 1-1/8 wrenches or sockets
1-1/2 socket with long extension
½ in. Allen drive
Cotton wipes
Cotton swabs
Cleaning solvent (e.g. isopropyl alcohol)
Bore brushes and push rods
12 mm deep socket
10 mm wrench or socket
Flexible tape measure
1 m long ruler
4 in. wide Kapton tape
Vacuum grease
Appropriate torque wrenches

Basic Parts List
Machined parts:

- Tube
- Top cap (vent end)
- Bottom cap (igniter end)
- 2 ea. clamping plates
- 8 ea. Standoffs
- Top blast shield
- Bottom blast shield assembly
- Heaters
- Threaded rods and hardware

M5 lockwashers
M5 female standoffs
Crimp ring terminals, 10-12 gauge wire for #10 screw
M5 x 10 mm SHCS
Glow plugs
O-rings

1 EXPERIMENT ASSEMBLY

1. Prepare **igniter end cap** subassembly.
    1.1. Check and record electrical resistance of two glow plugs. Nominal resistance should be around 0.8 ohms.
    1.2. Install two glow plugs into the **igniter end cap (bottom cap)** avoiding cross-threading**.** Torque glow plug to 10-15 ft. lb. using 12 mm deep socket.
    1.3. Orient **igniter end cap** cavity upward and cover an area roughly 4 inches in diameter (centered around thermite cavity) with Kapton Tape.
    1.4. Use a razor to trim away the Kapton spanning over the thermite pocket (leaving a Kapton layer around the thermite pocket including the shallow counterbore around the thermite pocket)
    1.5. Fill cavity in end cap with thermite so the thermite is level with the rim of the shallow counterbore. Use a flat plastic disc to flatten and smooth top surface of thermite. Note: It is useful to build/function a test igniter before building the igniters used in the actual tests. Attempt to repeat the thermite packing density used in successful test-builds of the igniter.
    1.6. Remove Kapton tape surrounding the thermite pocket and clean any thermite outside the cavity.
    1.7. Cover thermite cavity with wide Kapton tape, pressing Kapton tape to seal on the counterbore lip with cotton Q-tip. The purpose of this is to allow the igniter end cap to be handled in any orientation without spilling the thermite.
    1.8. Trim Kapton tape at the outer diameter of the counterbore lip and run a Q-tip over the edge of the Kapton covering to ensure good adhesion.

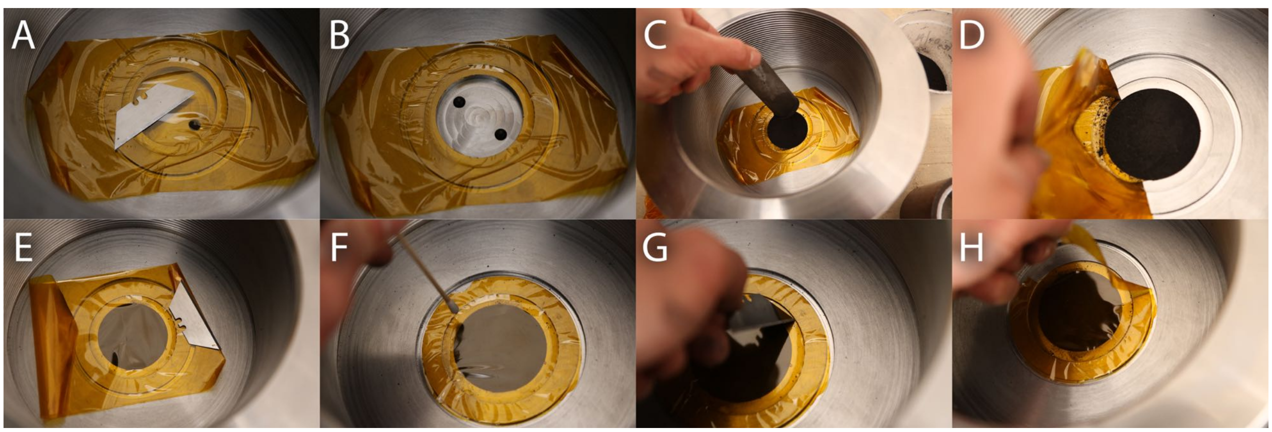


Figure 76 Progression of Thermite Igniter Assembly (*alphabetical order*)

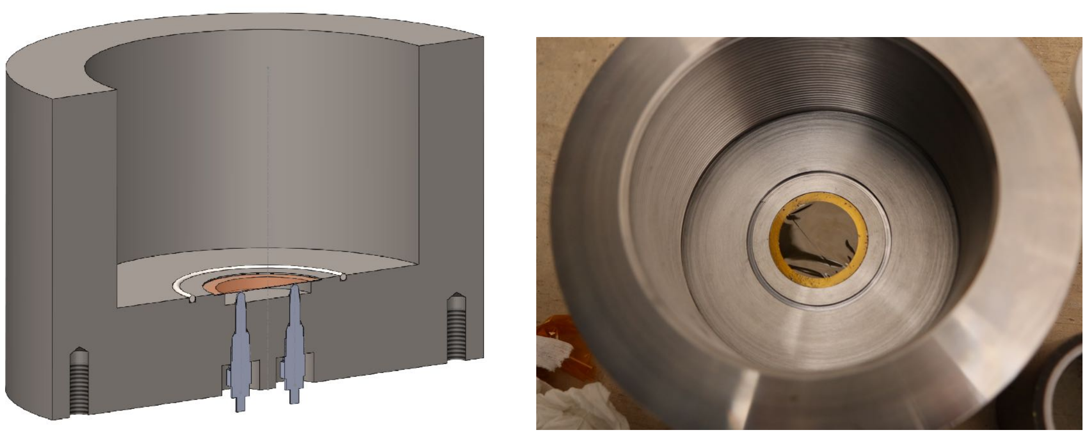


Figure 77. Left: Cutaway view of assembled igniter end cap subassembly (thermite not shown). Right: Thermite installed/taped in igniter.

    1.9. Wait to insert O-ring until **igniter end cap** is installed to the main **tube**.
2. Prepare thermocouple feedthrough subassembly.
    2.1. Test 4X Omega part TJC36-CAXL-020G-12-SMPW-M thermocouple probes by connecting each to a TC reader and apply/remove a mild heat source (in this case fingertip) to observe TC is functioning properly.
    2.2. Insert the 4 tested TCs through the following components in order (and in orientation seen in Figure 78)
        2.2.1. A) Autoclave Engineers clamping nut (AGL-40)
        2.2.2. B) custom drilled Autoclave Engineers plug

2.3. Label thermocouple wires at the electrical-plug-ends of the TCs.
2.4. Extend thermocouple probe tips out beyond the tip of the drilled plug and secure them to the corresponding machined track in the "Internal TC Brazing Fixture" (small aluminum bushing seen in Figure 78 *left* is used to compress the bunch of TC probes). The brazing fixture ensures the TC tips are beyond the tip of the drilled plug by the following lengths:
   2.4.1. TC1 2.969 in.; TC2 2.569 in; TC3 2.169 in; TC4 1.769 in.

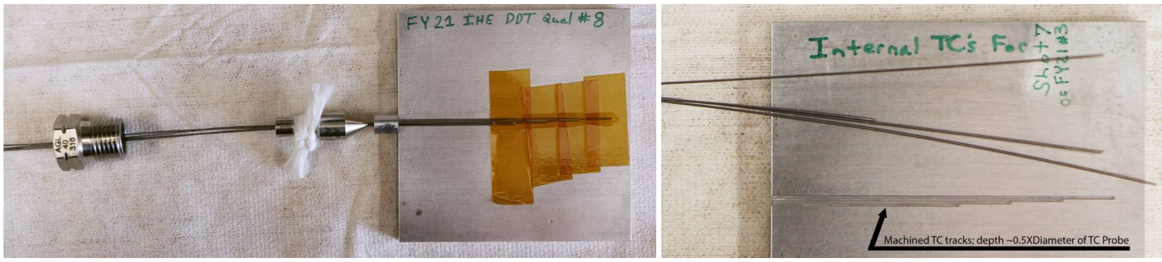


Figure 78 Internal TCs attached to brazing fixture

2.5. Wrap/tie a small length of fiberglass cord as see in Figure 78 to protect the tapered-surface of the custom drilled plug closest to the AGL-40. This helps to avoid getting slag on this sealing surface during brazing operations. Additional option in future could include (but not limited to) removable/breakable high temperature bushings, fiberglass, or two-piece shaft collar.
2.6. Maintaining probe lengths, braze TC probe wires into feedthrough plug.
2.7. Remove fiberglass, excess braze, or slag material that would prevent the proper seating of the AGL-40 nut with the plug.
2.8. Test and record that thermocouples are operating properly after being brazed into plug.

3. Build firing site block house (purpose of block house is to mitigate possible metal fragments that would start a brush fire off the firing mound), with the following features:
   3.1. 4 ft. thick concrete blocks comprising a main house with a roof of steel and sandbags that will remain in place for multiple shots (only rebuilt as necessary).
   3.2. The blockhouse design actually used in FY20 and FY21 consists of a main blockhouse with an attached hallway entrance (see Figure 79). An alternative design is to replace the hallway with a simple removable block wall that must be built after the shot is emplaced in the main blockhouse.
   3.3. One or two layers of ¾-in. plywood is set atop the leveled sand to act as a working floor; for assembly work and movement of the shot (stand must be able to roll into and out of blockhouse). NOTE: A possible improvement to this method is to replace the plywood with ~½" steel plate to achieve a non-flammable hard floor to work on.
   3.4. Place sandbags in appropriate spots of the blockhouse to arrest/impede primary fragments with line-of-sight escape paths out of the blockhouse (including stacking sandbags on the roof).

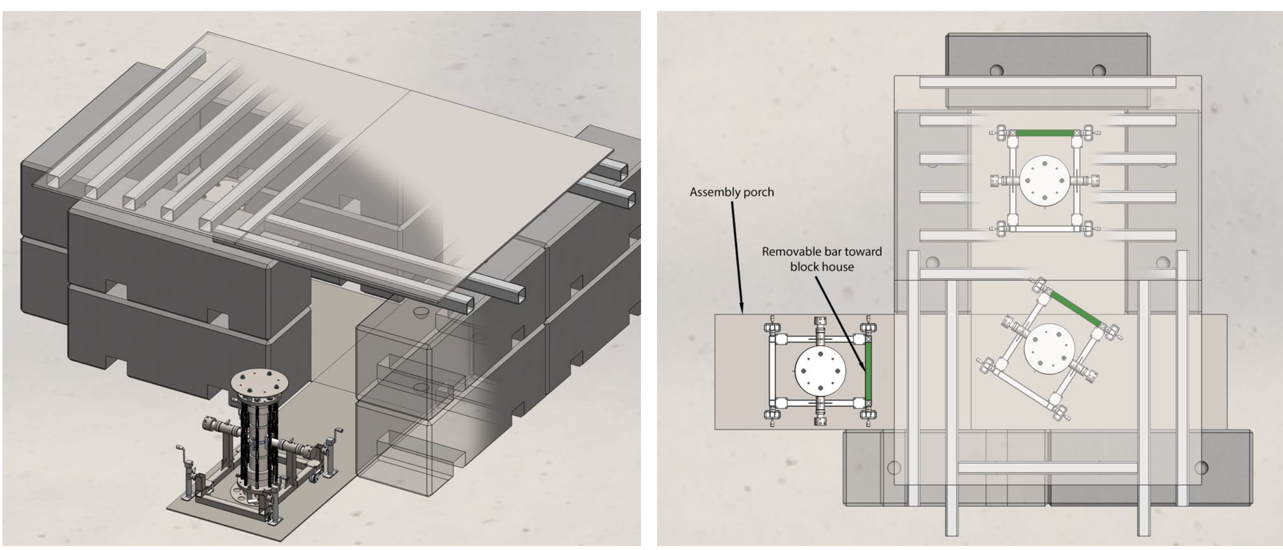


Figure 79. Firing site blockhouse in configuration with hallway entrance (shot assembly shown)

4. Move empty assembly fixture onto side porch, with the removable bar on the assembly fixture oriented closest to the block house (see Figure 79). NOTE: Assembly stand has only ONE removable crossbar and it MUST BE ORIENTED TOWARDS THE BLOCKHOUSE. This removable bar will allow the assembly stand to be rolled out of the blockhouse after the shot is left freestanding inside the house.

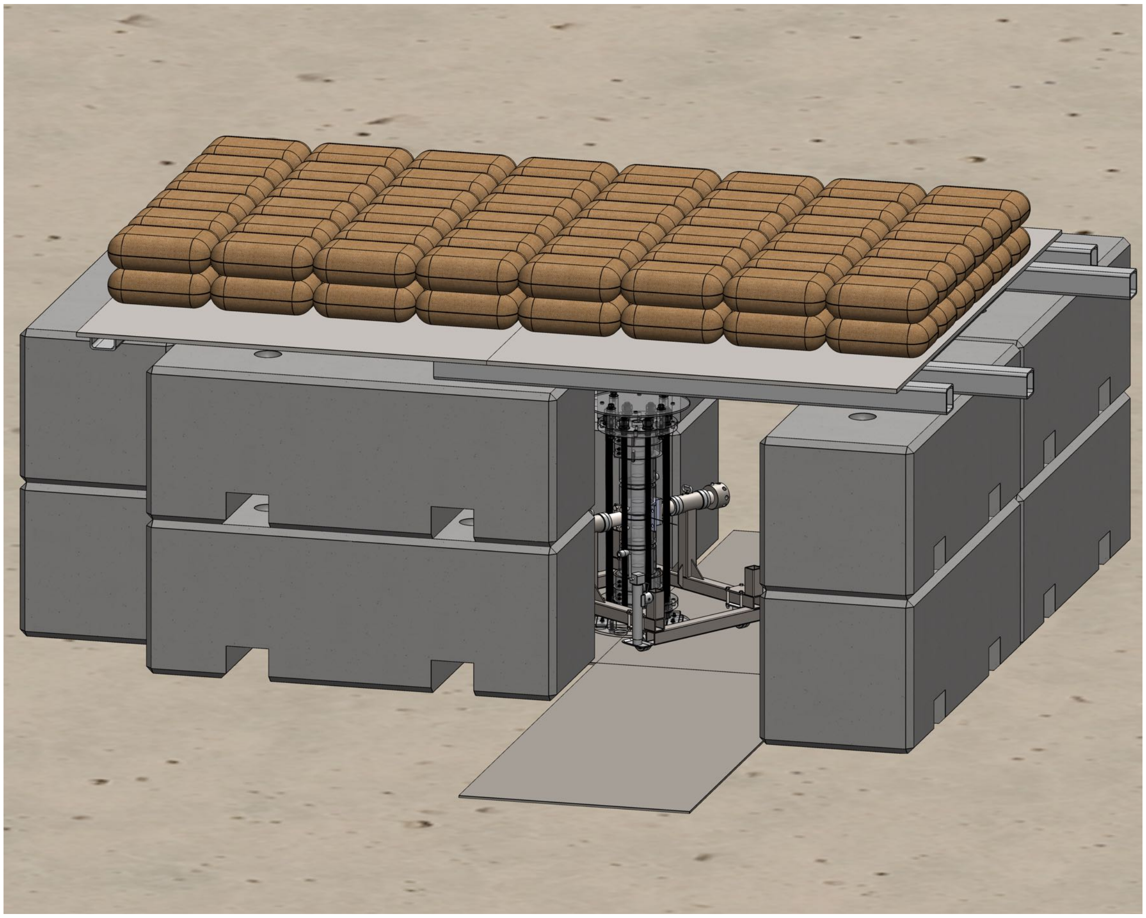


Figure 80 Blockhouse shown with sandbags over steel constructed roof

5. Prepare assembly cradle
   5.1. Bolt supporting crossbar to stand.
   5.2. Install two of the **quarter clamp** sections. Install bolts with ≈ 1/16 in. gap remaining (allowing slight amount of movement of the **quarter clamps)**.
      5.2.1. 2 ea. ¾-10 UNC x 2.25 hex head bolts and ¾-10 UNC nuts for bolting clamps to each other
      5.2.2. 4 ea. ¾-10 UNC x 1.5 hex head for bolting clamps to stand mating plates
6. Retract trailer jacks until stand is resting on wheels rather than jacks, for most control over positioning.
7. Pivot the cradle so that the clamp sections are concave up parallel with floor, to receive the center tube horizontally.
8. Install **steel pivot pins** to prevent the cradle from rotating. ENSURE THE PINS ARE INSERTED TO FULL DEPTH AND THAT THE PIN LENGTH IS AT LEAST 4 INCHES LONG.

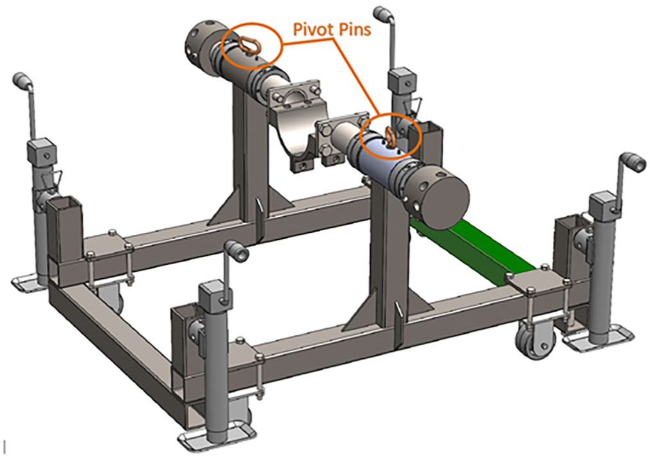


Figure 81. Cradle ready to receive tube.

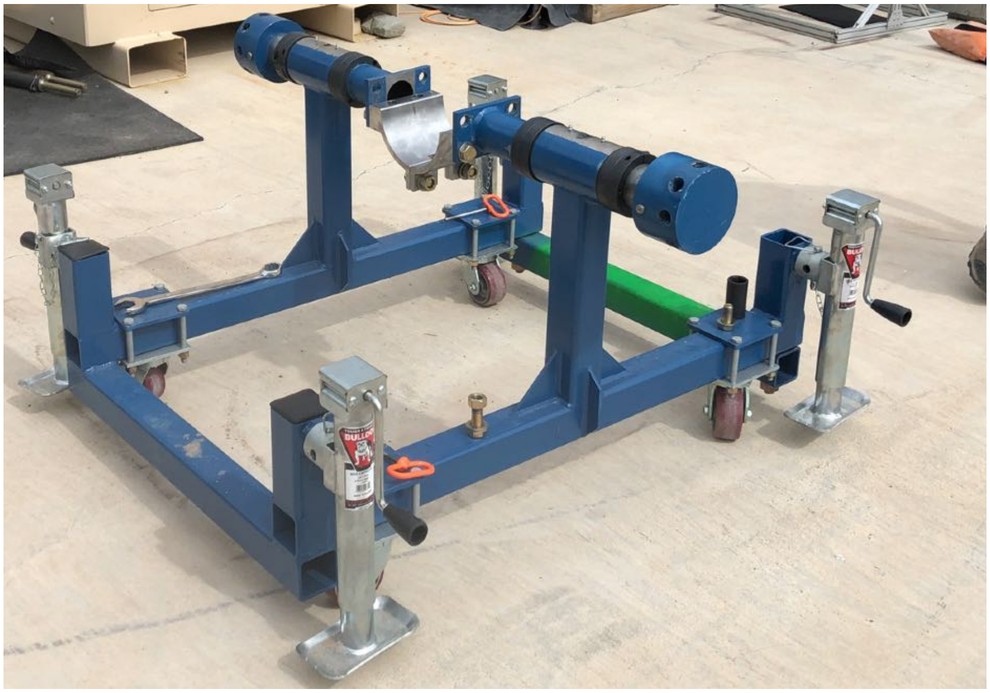
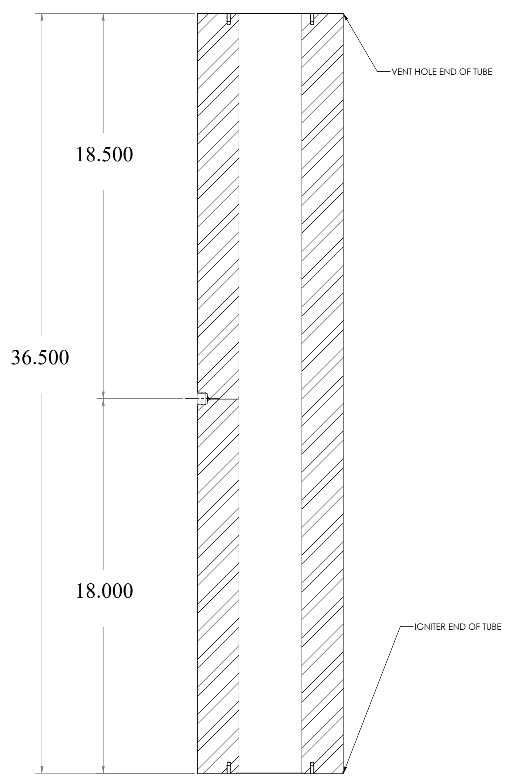


Figure 82. Photograph of cradle ready to receive tube.

9. Identify tube ends
   - 9.1. Measure the distance from each end of the **tube** to the center feedthrough. The end that is closest (18 in.) away from the center feedthrough is the igniter cap end of the tube (eventually will be the bottom end once flipped vertically). Note: The vent end is 18.5 in. away from the center feedthrough.
   - 9.2. Mark the tube on the outside surface on each end with sharpie, "igniter cap end" and "vent cap end".



9.3. Use either a forklift or crane to place tube into cradle (execute either "option 1" or "option 2" steps below):

9.3.1. Option 1: using forklift (used in FY20 and FY21)
   9.3.1.1. Separate forklift tines so that there exists a gap of >6 inches between the tines. The outside dimension of the tines can be no more than 40 inches.
   9.3.1.2. Four ≈ 6 in. C-clamps total will be used to secure tube from rolling on to forklift tines. Clamp one c-clamp to each forklift tine, at a position to chock the tube to prevent it from rolling towards the forklift.
   9.3.1.3. Position forklift tines level with bottom of tube as it rests on the pallet.
   9.3.1.4. Recommend donning leather gloves and be mindful of opportunities that would cause crush/pinch.
   9.3.1.5. Roll/transfer the tube from the pallet onto the forklift tines. Pry bars can be used to aid in this process.
   9.3.1.6. Roll the tube up against the c-clamps.
   9.3.1.7. Install another c-clamp on each of the forklift tines at the front side of the tube, to prevent it from rolling off the tines (away from the forklift).

9.3.2. Option 2: using crane
   9.3.2.1. Pass crane lifting strap through the center bore of the tube. Use chafe protection as necessary where the strap contacts the end edges of the bore.

9.3.3. Lower tube towards assembly cradle.

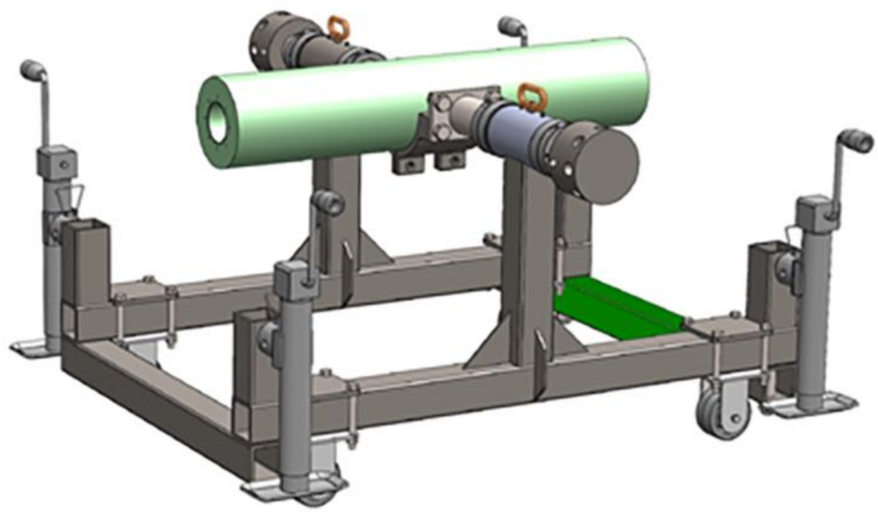


Figure 83. Tube resting in cradle. At this stage, the forklift tines or crane will still be in position (not shown here). Center tube is shown in green in all illustrations only to highlight the main component for visual clarity.

9.3.4. As the tube is lowered towards the cradle, the central feedthrough hole through the side wall of the tube must line up with the square access hole in the cradle (Figure 84. View of feedthrough hole aligned with square hole.).

9.3.5. NOTE THAT HOLE IS NOT CENTERED END-TO-END IN THE TUBE. To reiterate: the hole is closer to the ignition end of the tube. If a particular final orientation of the tube, relative to the stand, is desired (based on firing site specifics), take note of the igniter end and which direction it faces when placed in the cradle.

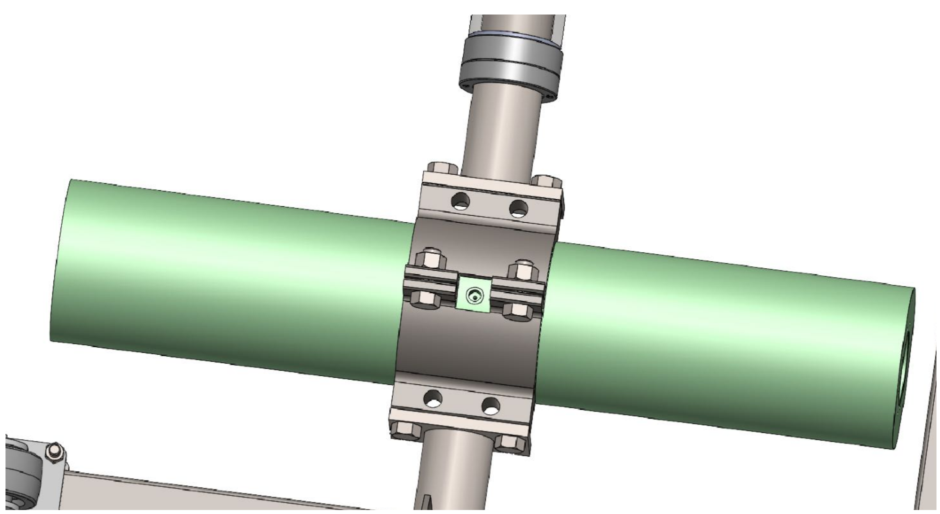


Figure 84. View of feedthrough hole aligned with square hole.

Figure 85. Photograph of feedthrough hole aligned with clamp quarters.

9.3.6. The position of the stand, forklift/crane, or tube on forklift/crane can all be nominally adjusted in order to achieve alignment of the tube as it is lowered.
9.3.7. While maintaining alignment, lower the tube so that the weight is just barely resting entirely on the cradle clamps, and weight is just barely removed completely from forklift tines.
9.3.8. Maintain forklift tines/crane in this position (where weight is barely fully-transferred), until clamp is fully secured.
9.3.9. Make final adjustments to the position of the tube to center feedthrough hole in the clamp quarter access square. A strap/chain wrench and dead blow (non-marring) hammer may help this process.
9.3.10. When all is aligned, install final two quarter clamps in place. Install bolts with ≈1/16 in. gap (do not tighten until everything is positioned).
9.3.11. Add and hand tighten the following fasteners:
  9.3.11.1. 4 ea. ¾-10 UNC x 1.5 hex head bolts using 1-1/8 in. wrench (for bolting clamps to stand mating plates)
  9.3.11.2. 4 ea. 5/8-11 UNC x 4.5 SHCS (1/2" hex key drive) with 5/8-11 UNC nuts (15/16 in. wrench) for clamping top half to bottom half of clamp pairs
  9.3.11.3. Additional 2 ea. ¾-10 UNC x 2.25 hex head bolts and ¾-10 UNC nuts using 1-1/8 in. wrenches for bolting clamps to each other

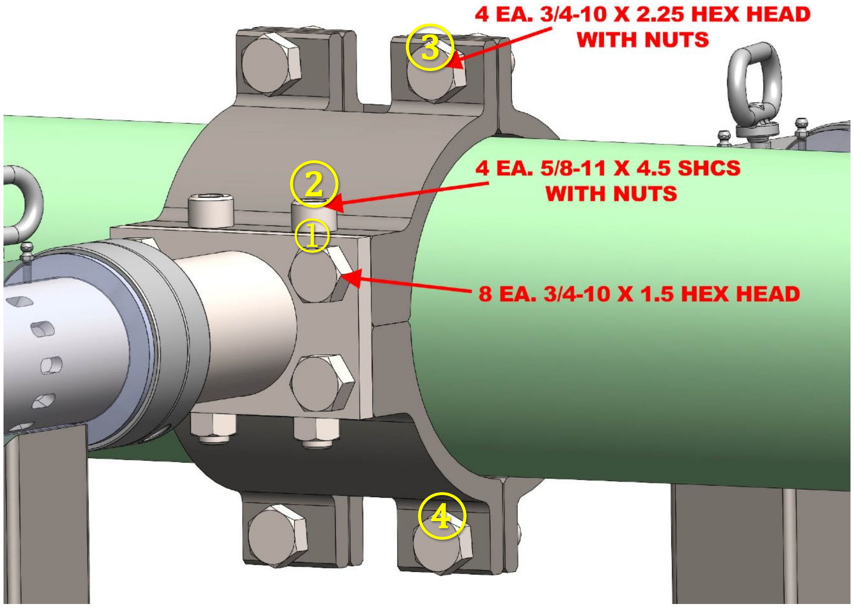


Figure 86. Identification of bolts used on clamps.

9.3.12. Confirm proper final alignment. In the numerical order, starting at ① (as seen in Figure 86) begin tightening the fasteners that are performing the same function (meaning **all** ① ¾-10 X 1.5" fasteners are tightened, then followed by **all** ② 5/8-11X4.5", followed by ③ and ④). Fastener torque should be ~50-60 ft.-lbs.

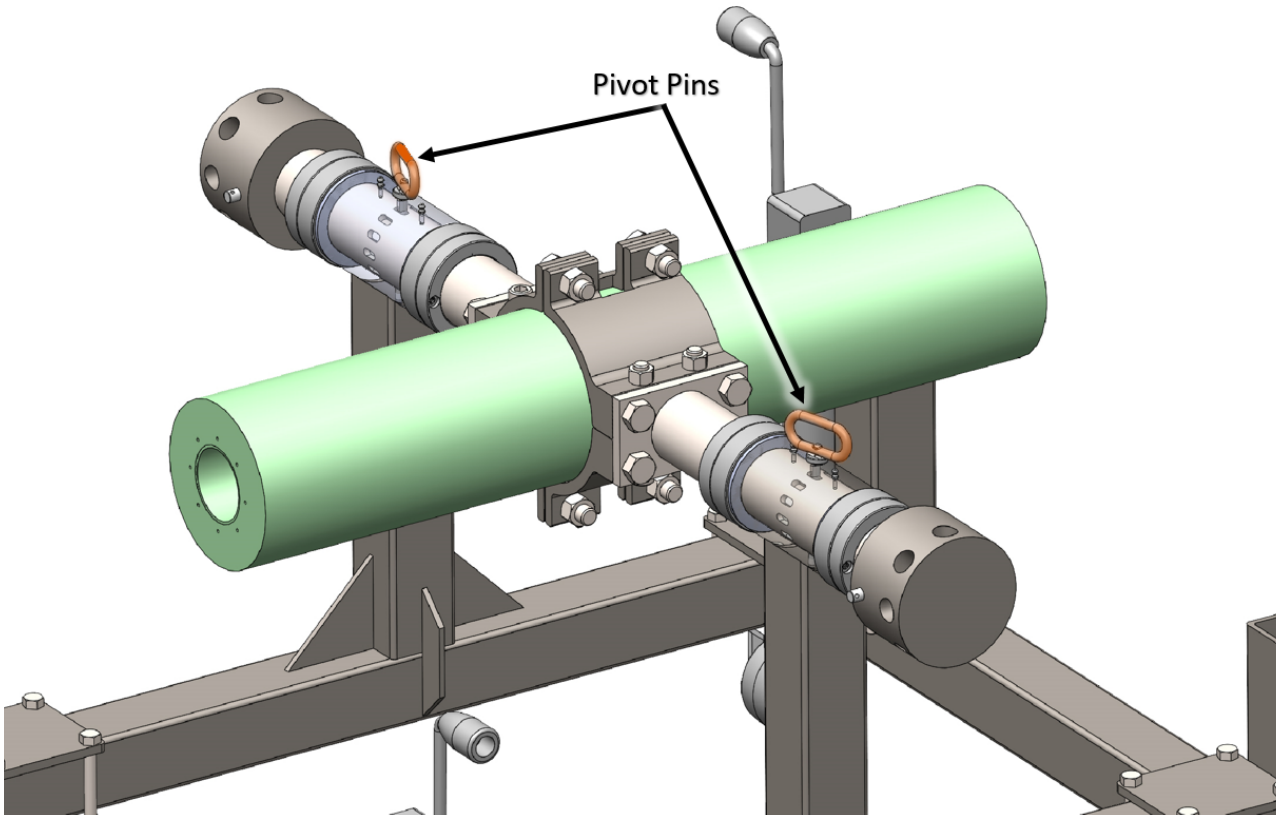


Figure 87. Tube fully clamped. If pivot pins are fully inserted, forklift/crane can be removed at this point.

9.3.13. Confirm that pivot pins are fully inserted as seen in Figure 87, to prevent cradle from rotating.

10. Fully remove the forklift from the assembly.
11. Fully lower trailer jacks so that the assembly stand is no longer on the casters.
12. Clean internal-TC feedthrough-bore into center bore of main tube with an appropriate solvent (ethanol or isopropyl worked well) and a small plastic-bristle tube cleaner. Blow feedthrough dry with canned air ensuring no alcohol, oil, or solvent is left in the cavity.
13. Clean bore of center tube using rags and appropriate solvent to remove machining oils and dust/debris. Ensure no solvent or alcohol is left in tube after cleaning. NOTE: if tube is not used relatively immediately, re-oil the inner surface to prevent rusting (cleaning steps will need to be repeated before next test execution is attempted).
14. Tape the vent end (non-igniter end) of tube to prevent dusk from entering the tube. Also protect the large tube threads with a bag or tape to avoid grit adhering to the threads.
15. Rotate center tube so that igniter end is upward.

15.1. Sub-procedure for rotating tube

15.1.1. Insert **rotation handles** into the **sockets**. Secure with **cotter pins**.

15.1.2. One worker takes control of each **rotation handle**.

15.1.3. Third worker removes both **pivot pins**, allowing the tube to be freely rotated.

15.1.4. **Once pivot pins are removed, at least one rotation handle must be in position, secured with the cotter pin at all times.** This is to remove the possibility that workers could lose control of the assembly rotation, allowing it to pivot uncontrolled.

15.1.5. Workers move rotation handles to rotate center tube to desired orientation (in this case so that igniter end is upward).

15.1.6. It will be necessary to remove and reposition rotation handles in a new hole in the socket. Insert at least one pivot pin, and remove/reposition rotation handles one at a time. Cotter pin is replaced each time after rotation handle is inserted to ensure that the rotation handle cannot come out unexpectedly.

15.1.7. Remove pivot pin(s) again to allow rotation.

15.1.8. When center tube is positioned as desired, third worker replaces both pivot pins. Workers manning rotation handles may then release rotation handles. Remove rotation handles.

16. Test install **igniter end cap assembly** onto **center tube** for checking distances.
    16.1. Coat threads of center tube with high-temperature anti-seize. NOTE: use of too much anti-seize can cause significantly increased threading resistance.
    16.2. Lift igniter end cap assembly and rest on top of center tube, cavity downward.
    16.3. Carefully rotate the end cap CW and/or CCW until you feel the end cap find the first thread on the center tube.
    16.4. Using a paint or sharpie marker, draw a “start” reference mark on the igniter end cap and center tube (to help observe the number of rotations it takes to fully thread the igniter end cap onto center tube). Thread cap onto tube until hand tight (a cheater bar may be needed to overcome threading resistance with anti-seize. Count and record the number of turns it takes to bottom-out.

Figure 88: Test installation of end cap (left to right)

    16.5. Mark final position/alignment of cap with tube, with both horizontal and vertical marks.
    16.6. Unthread cap completely. Note: Utilize the knowledge of the number of turns it took to install end cap to know when you are nearing the fully unthreaded state of the end cap.
    16.7. Install O-ring
        16.7.1. Coat O-ring liberally with thick vacuum grease so that it stays in groove.
        16.7.2. Photograph interior with O-ring in place (to document that it was done).
    16.8. Thread cap back onto tube (counting number of turns that it takes).
    16.9. When cap comes hand-tight, measure arc-length on tube between the fiducial marks and make note.
    16.10. Thread two grade 5 bolts, 180 degrees apart, in the end cap. Fit a breaker bar between the two bolts to be able to apply further tightening torque to the end cap. Make note of final arc-length between fiducial marks.

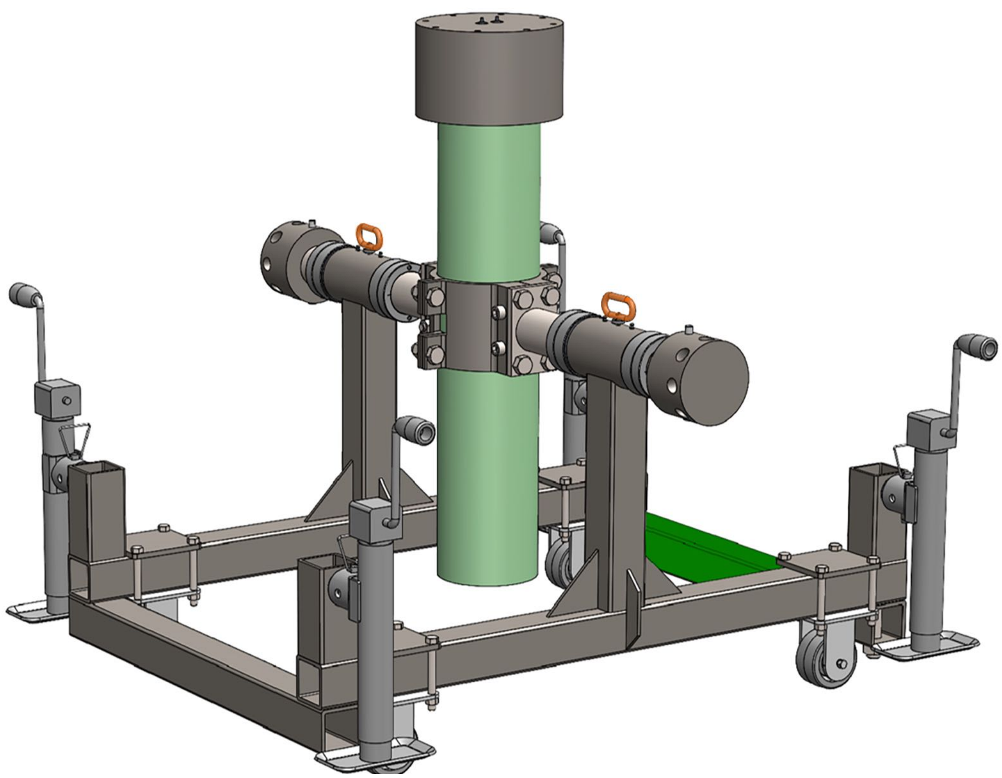


Figure 89. Igniter end cap installed.

17. Install **clamping plate** to igniter end.

17.1. Lift clamping plate (with orientation of the large counter bore facing downward) on top of igniter end cap, carefully aligning through holes for the glow plugs to avoid damage to the glow plugs
17.2. Bolt clamping plate to end cap using 8 ea. ½-13 x 2.25 hex head bolts (and appropriate plain and lock washers); torque to 32 ft.-lbs.
17.3. NOTE: In FY20 and FY21, it was determined to be more efficient/clean to complete this initial part of the assembly (section 5 through to current section) on the skid-testing pad (a large concrete working pad) rather than assembling on the firing point. The assembly (ignitor only present; no HE) is transported in vertical orientation up on to the point and placed on the porch of the block house for the remaining assembly steps.

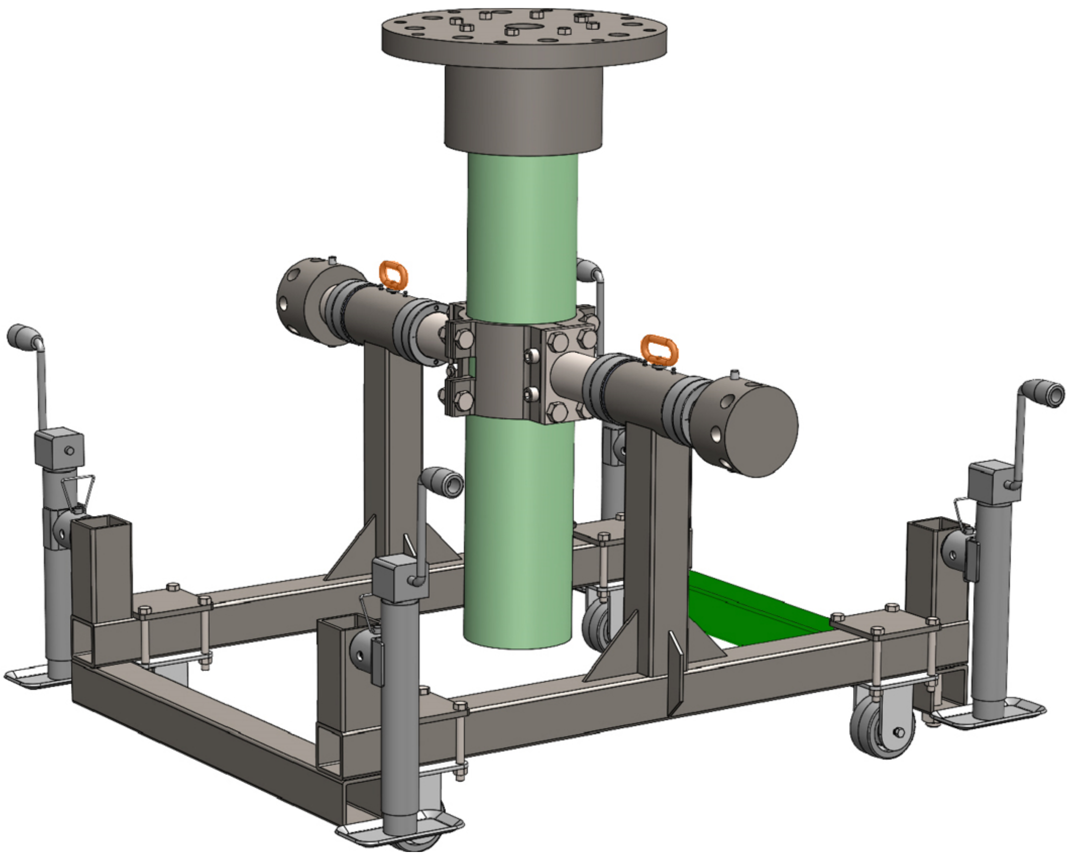


Figure 90. Clamping Plate installed on threaded igniter end cap.

18. Connect glowplug assembly and wiring.
18.1. Fasten female-threaded hex standoffs (McMaster 94868A638) (glowplug is M5x0.88) to each glow plug electrical stud with an M5 lock washer (ensure lockwasher is fully compressed). Snug using a 10 mm wrench or socket. NOTE: **be careful to not over torque this item** as the internals of the glow plug can be damaged; resulting in the need to re-build the ignitor cap assembly.

Figure 91. Stack-up of parts for glow-plug electrical connections.

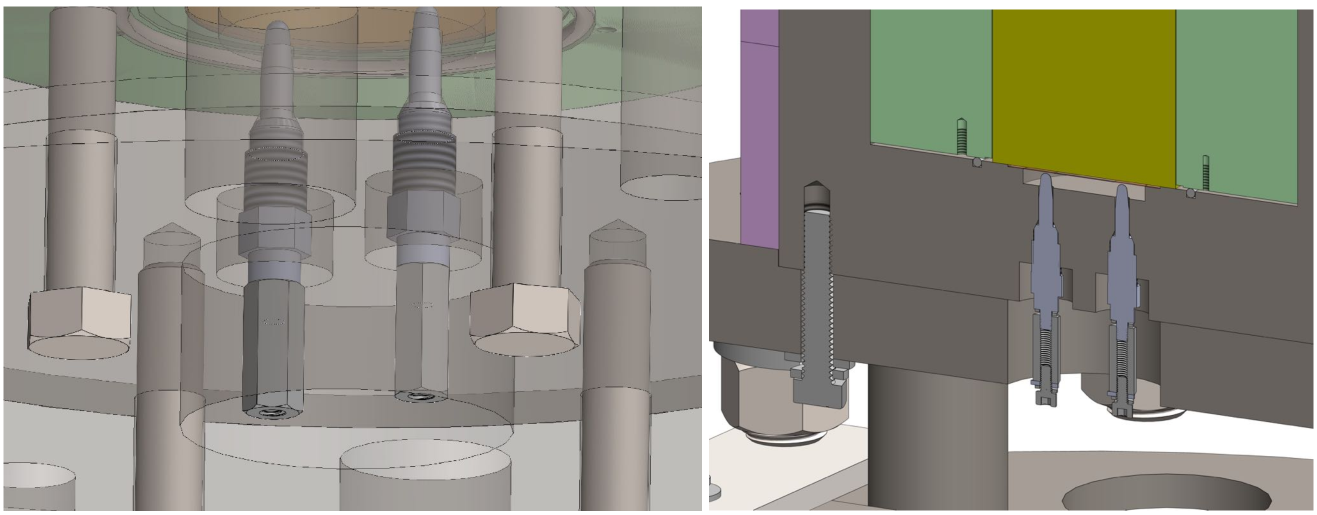


Figure 92. ***Left:*** **Baseplate and end cap metal is transparent to show the female-threaded couplers installed on glow plugs.** ***Right:*** **Cutaway view**

18.2. Fasten a ~10 ft. length of insulated14 gauge or larger wire (ring-terminal terminated) to each of the female threaded hex standoffs using M5x0.88 x 10 mm long SHCS with lock-washers. Strain relieve and tape wires out of the way to the tube for later connection.

19. Fill tube with explosive

19.1. Option A: solid pellets

19.1.1. Rotate the assembly so that the center tube is horizontal, following 15.1 **Sub-procedure for rotating tube**.

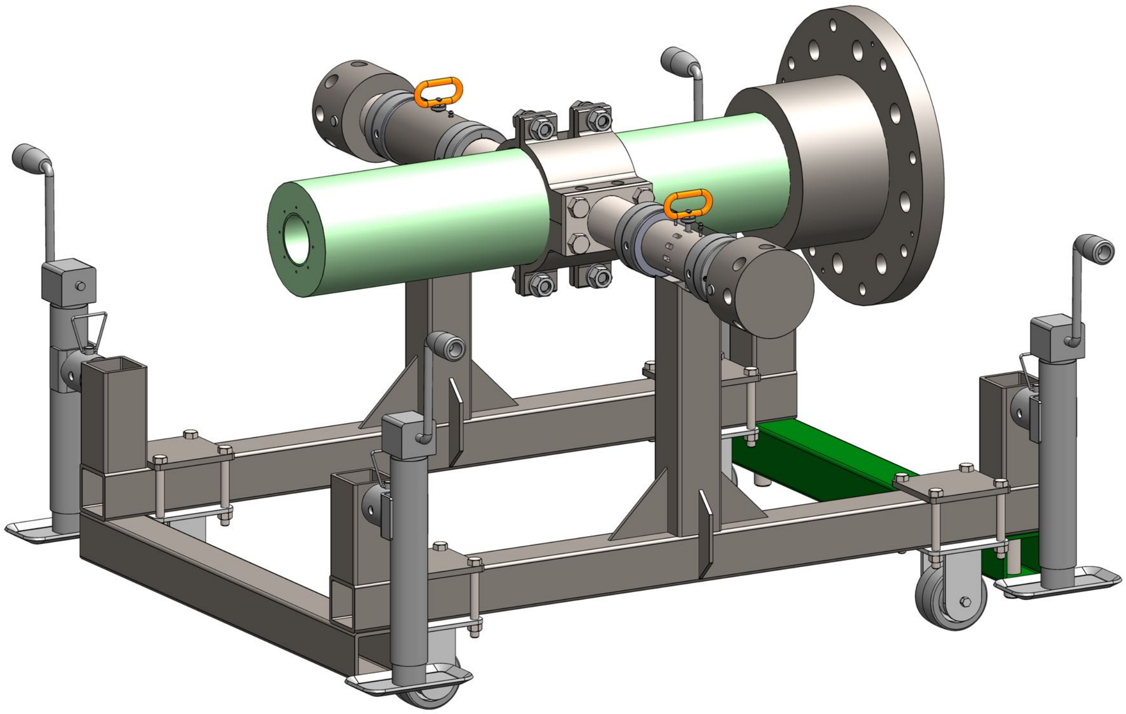


Figure 93. Tube rotated for filling with pressed pellets.

19.1.2. Remove tape/bag protecting tube end and threads. Re-inspect bore visually for debris. Fill tube halfway with explosive.

19.1.2.1. Insert 6 pellets total, one-by-one. Use pellets with lengths that average out to 3.000 inches each. Record the length of each pellet to be used in the assembly. Total length of the 6-pellet column should be ≤18 in. for thermocouples to properly align. Inspect each HE piece to ensure no flashing will prevent proper stack-up length.

19.1.2.2. **Slowly** push each pellet all the way to the bottom using plastic or wooden rod as they are inserted. It helps to wrap a rag around the front of the push rod to avoid damaging the HE while pushing down tube or pushing to ensure proper seating.

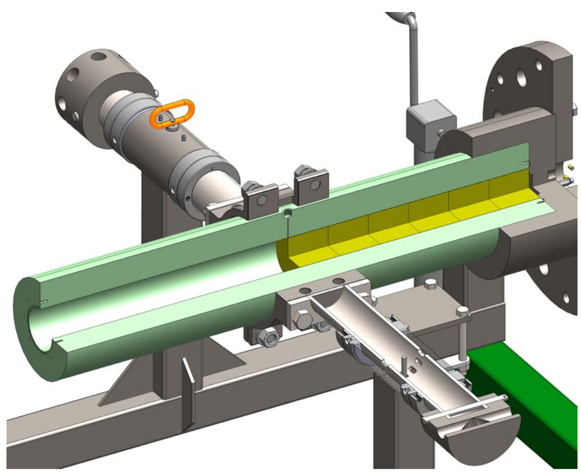


Figure 94. Cross-section view of horizontal tube half-filled with pellets.

19.1.3. Install thermocouple feedthrough subassembly.

19.1.3.1. Carefully guide thermocouple probe tips into feedthrough hole and into center bore of tube. Probe wires should enter tube just above the already-filled explosive. Carefully torque feedthrough clamp nut to 25 ft-lbs using a crowfoot wrench and torque wrench.

19.1.3.2. Strain relieve fragile thermocouple wires on the outside of the tube.

19.1.3.3. Document the thermocouples inside the tube with a photograph.

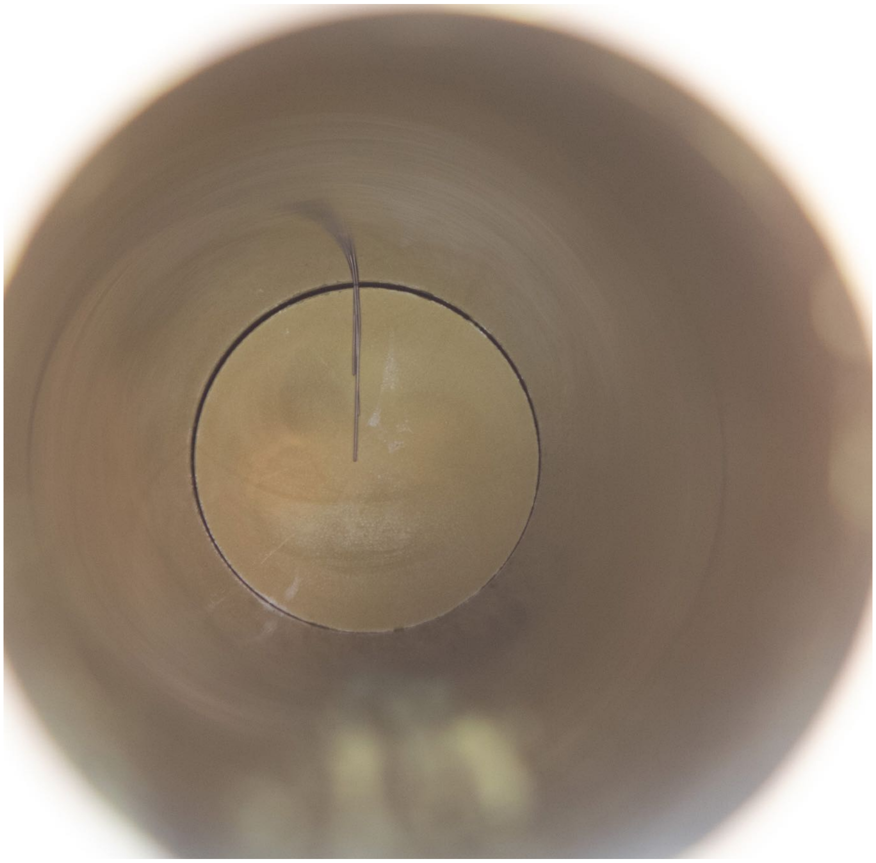


Figure 95. Photograph documenting the thermocouple positioning at the midplane.

19.1.4. Fill remainder of tube with 6 more pellets, keeping a running count of pellets as each is inserted.

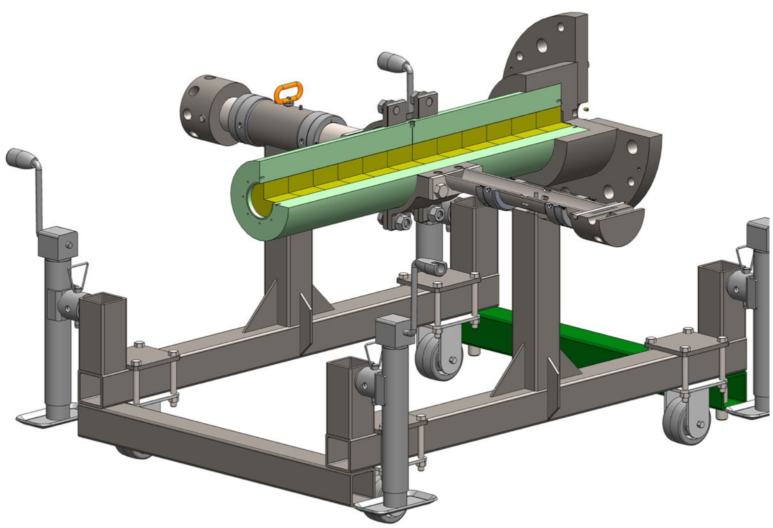


Figure 96. Cross-section view of horizontal tube fully-filled with pellets

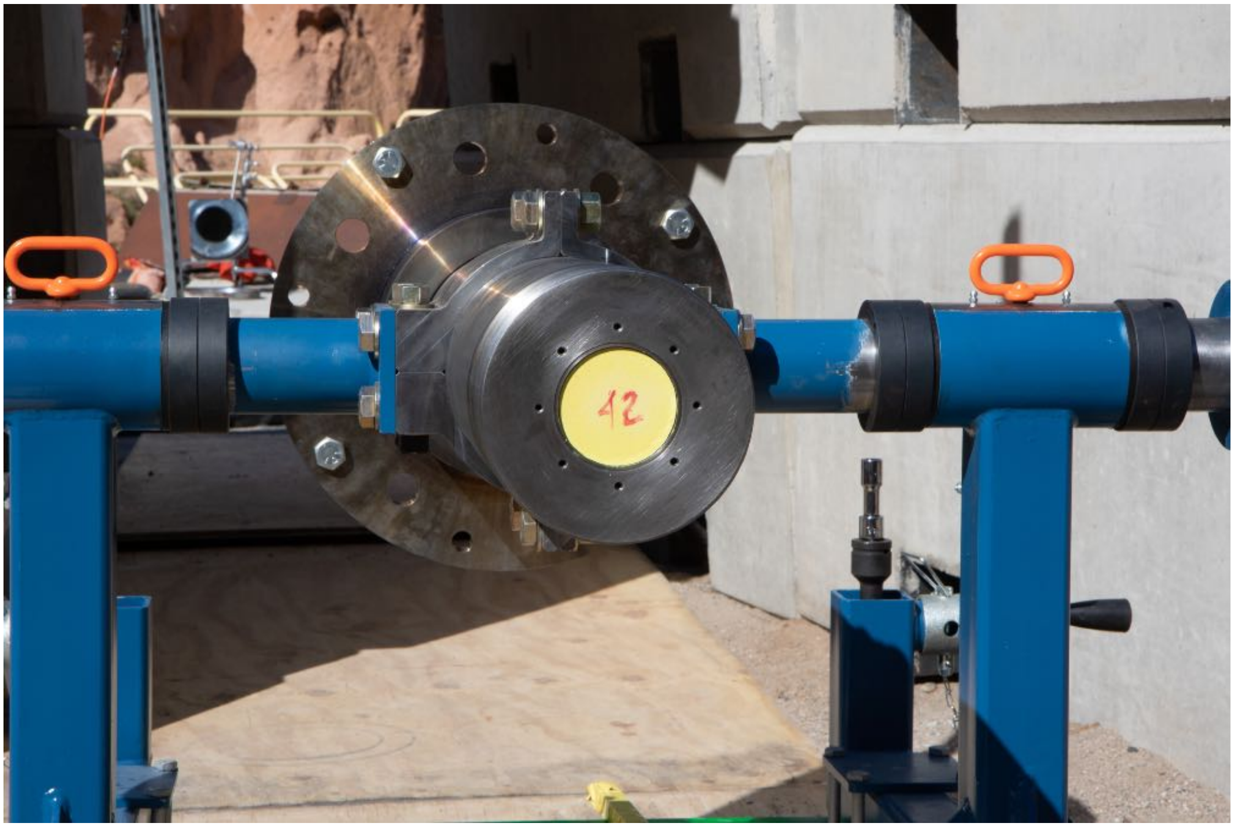


Figure 97. Photo of tube filled with pellets.

19.1.5. Measure and record the gap that remains between the 12th pellet surface and the metal lip of the bore.

19.1.6. Document the remaining ullage with a photograph.

19.1.7. Using wide Kapton tape; tape over end of tube. Then use 15.1 **Sub-procedure for rotating tube** in appropriate order to rotate the tube to a vertical orientation in such a way that the HE is **NEVER** downward as to fall out of the tube.

19.2. Option B: loose prills

19.2.1. Rotate the assembly so that the center tube is vertical, with the open fill hole upwards. Follow 15.1 **Sub-procedure for rotating tube**.

19.2.1.1. NOTE: Consider moving the assembly into the inside space of the block house for this operation (see future section 22 below **Roll stand into block house.)**

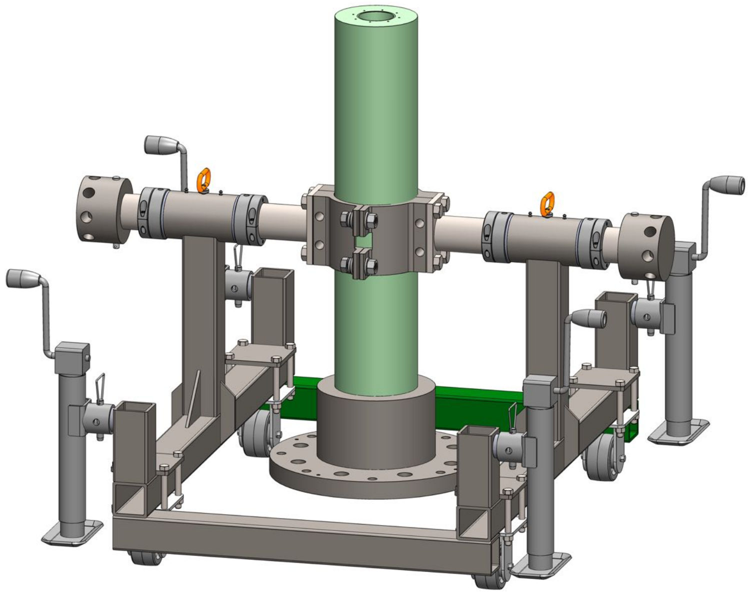


Figure 98. Tube rotated for filling with prills.

19.2.2. Transfer a known mass of prills to a supply source container, so that total mass of prills that goes into the tube can calculated at the end.

19.2.3. Fill tube halfway with explosive. Pour prills into the tube to a depth of 18 in. Appropriate depth can be monitored by temporarily inserting an indicator through the feedthrough hole into the bore (shining a flashlight through the feedthrough hole may help).

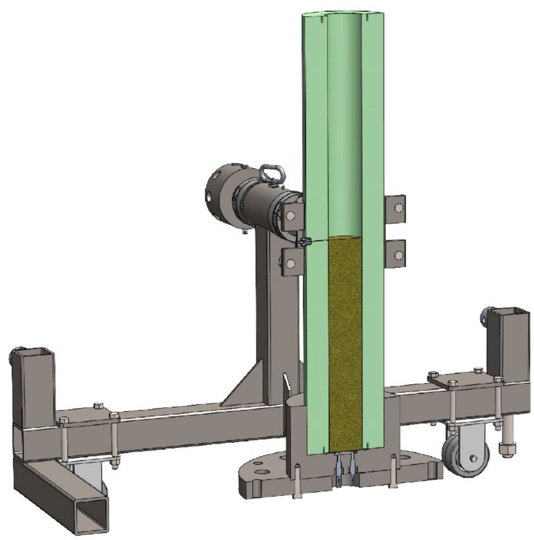


Figure 99. Cross-section view of vertical tube half-filled with prills.

19.2.4. Install thermocouple feedthrough subassembly.

19.2.4.1. Carefully guide thermocouple probe tips into feedthrough hole and into center bore of tube. Probe wires should enter tube just above the already-filled explosive. NOTE: clean/inspect cone and thread portion of tube (where internal TC assembly inserts and threads) to ensure no HE dust is on this surface.

19.2.5. Document the thermocouples inside the tube with a photograph and torque the feedthrough nut to 25 ft-lbs using a crowfoot wrench and torque wrench (Note: make sure to calculate the equivalent torque when using a crow-foot wrench).

19.2.6. Fill remainder of tube with prills, level with the top of the tube but with no part of the explosive extending above the top plane of the tube. Document the level with a photograph.

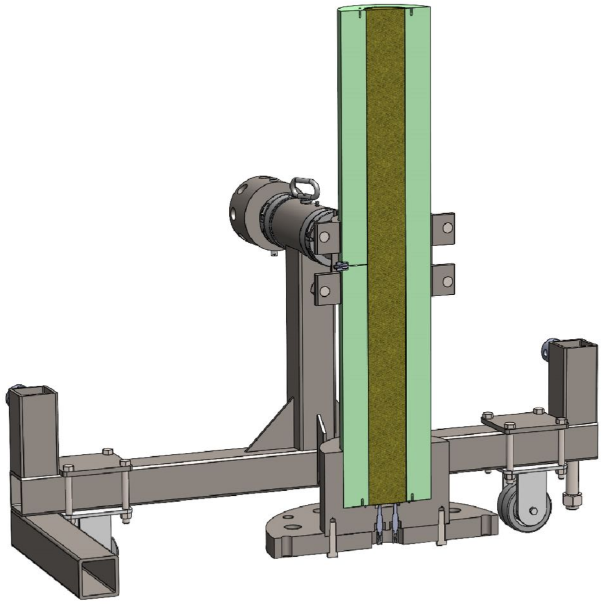


Figure 100. Cross-section view of vertical tube fully filled with prills.

19.2.7. After filling is complete, mass the unused supply source after tube is filled in order to obtain the net mass in the tube.

20. Tape over end of explosive with Kapton tape. Trim to the counterbore. Poke a small vent hole in the center of the Kapton tape for venting. Ensure no prills or HE powder has adhered to threads.

Figure 101. Photo of tube rotated.

21. Install vent cap
    - 21.1. Use same pre-installation procedure as found in section 16 to measure depth and alignment of cap without O-ring first.
    - 21.2. Mark fiducials and remove cap.
    - 21.3. Insert O-ring, generously coated with vacuum grease, into the groove.
    - 21.4. Photograph the interior showing the O-ring to record it was installed.
    - 21.5. Install cap, counting turns until hand tight. Record arc length between fiducial marks.

21.6. Use breaker bar to finish tightening. Record final arc length between fiducial marks.

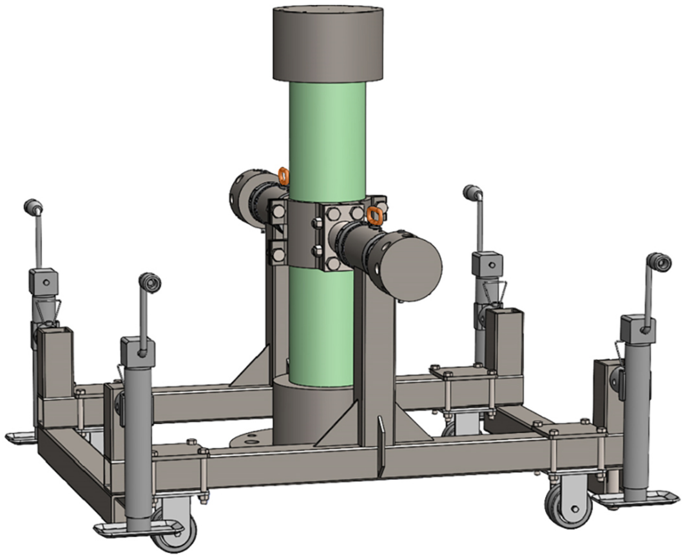



Figure 102. Vent cap installed.

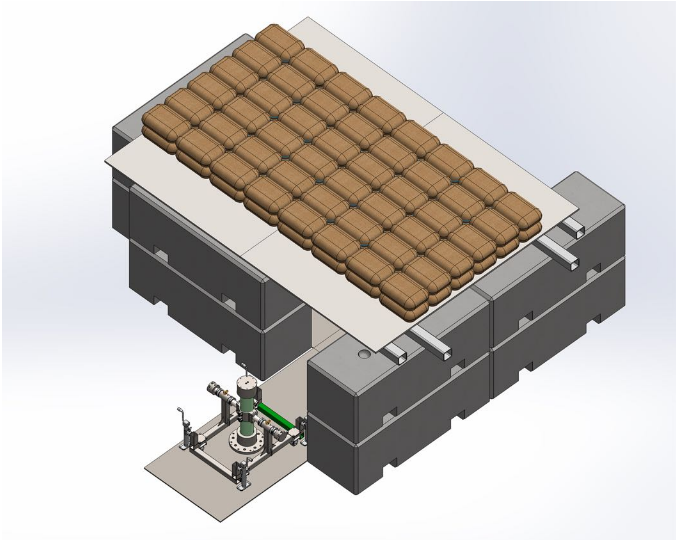


Figure 103. Illustrating assembled tube on the front porch.

22. Roll stand into block house.
    22.1. Retract jacks simultaneously until all casters rest on floor. NOTE: Be vigilant: stand could begin to roll/translate once more than two casters are contacting the ground.
    22.2. Stand can now be rolled to the desired firing location in the block house. Pry-bars and levers can help with this process.
23. Install **baseplate** to shot assembly
    23.1. Mount 4 ea. standoffs to baseplate with equal spacing. Use 4 ea. ¾-10 UNC x 1.75 hex head bolts with no washers and torque to 40-45 ft-lbs (see Figure 104 below).

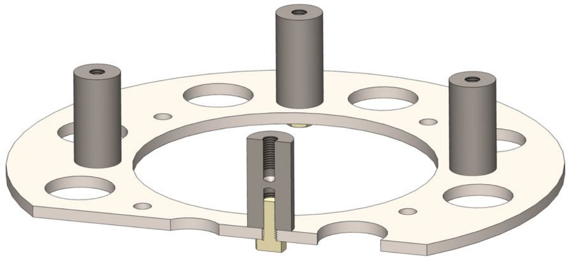


Figure 104. Baseplate with standoffs attached

Figure 105: Installing/torqueing standoffs to baseplate

23.2. Slide the torqued baseplate assembly under the experiment assembly (as seen in Figure 106) that is still in the assembly stand. The assembly may need to be lifted using the trailer jacks.

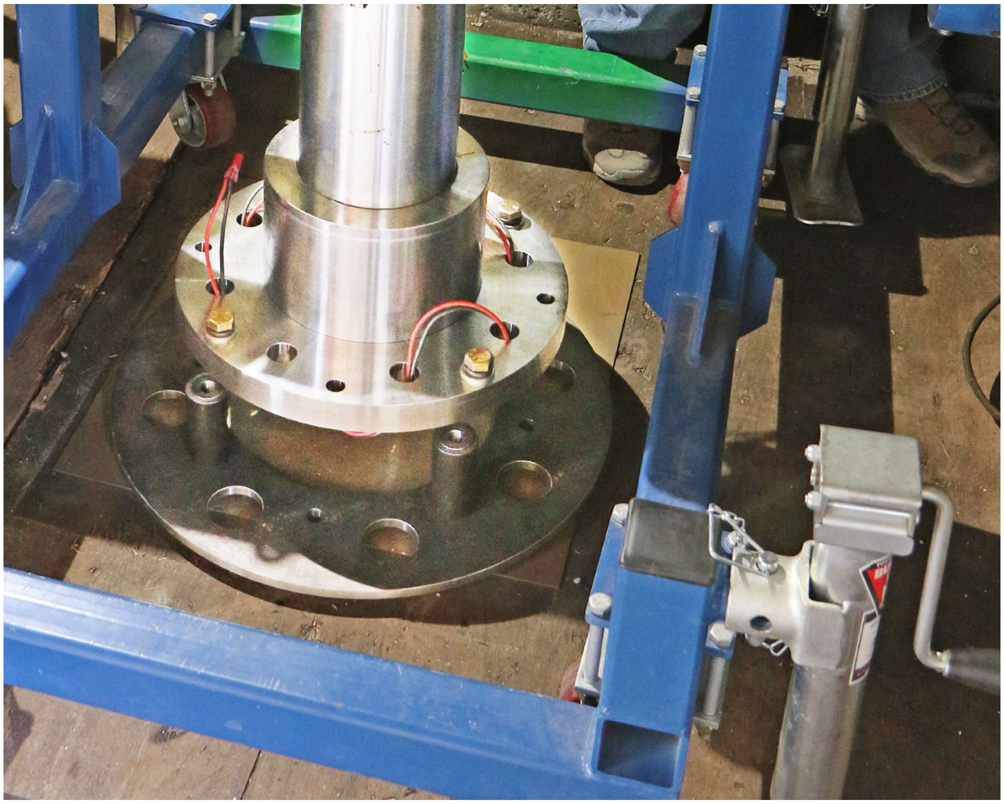


Figure 106: Installing baseplate assembly

23.2.1. Note the options for hole orientation, and install four standoffs evenly spaced.

23.2.2. Use 4 ea. ¾-10 UNC x 2.75 bolts (with appropriate plain and lock washers) to fasten standoffs to bottom clamping plate @ 40-45 ft-lbs. Use of pipe wrench on round standoffs is OK.

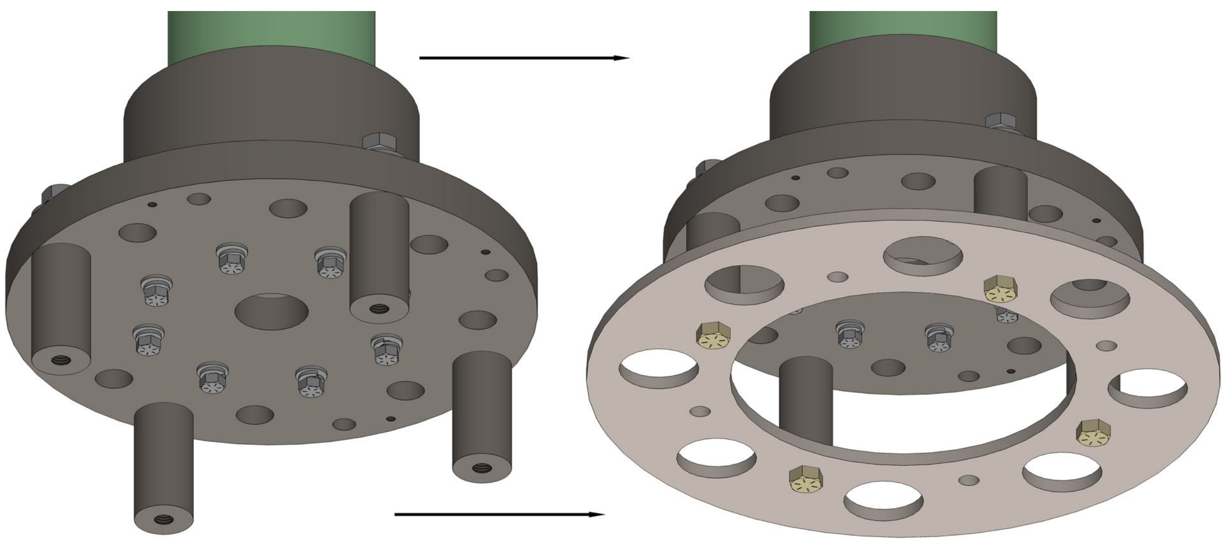


Figure 107. Alternative order of installation of standoffs mounted to clamping plate (OK but not recommended).

23.3. Retract jacks until tube assembly rests on floor. Extend just enough for weight of tube assembly to be transferred from stand to floor. Confirm that weight of tube assembly is completely transferred to floor by establishing ≈ 1/16 in. of air gap between jacks and floor (and that the casters are not touching the floor surface).

23.4. Unbolt clamping cradle on center of tube, **being particularly careful of fragile thermocouple wires**. If thermocouple wires are strain relieved to the cradle clamps, remove and transfer strain relief to the tube to avoid damage to wires.
23.5. Tube assembly should now be freestanding on the ground, free of the assembly stand.
23.6. Unbolt the removable square tube cross member on the assembly stand.

24. Roll empty stand out of block house and remove to a safe distance from shot, using lift gate of truck or forklift.

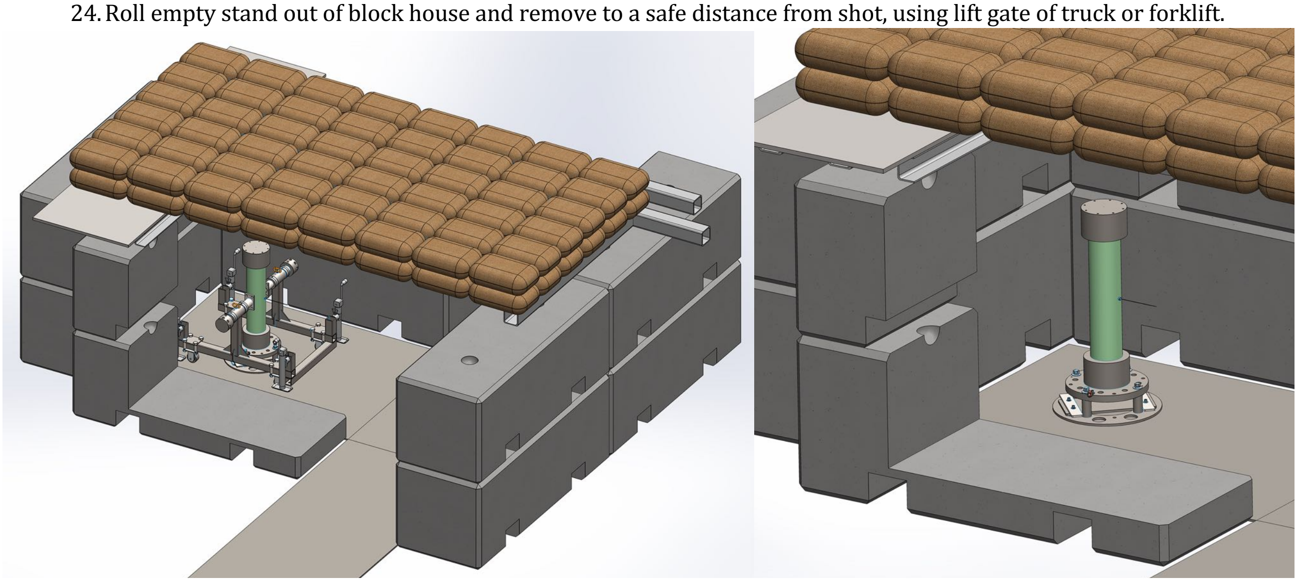


Figure 108. ***Left:*** **Shot placed into block house, stand cradle clamps and horizontal crossbar removed.** ***Right:*** **Stand rolled out of block house.**

25. Install **clamping plate** to vent end of assembly. *(NOTE: this clamping plate will be removed when the threaded rod is installed. The only reason that it is beneficial to install the clamping plate at this time is to give the worker who installs the heaters a reference plane that is 0.25 inches down from the vent end cap top-surface as seen in Figure 109. There are alternative methods that can accomplish this reference (such as a reference marks or appropriately designed stepped gauge blocks).*
25.1. Minimum two workers lift the **clamping plate** from ground level to above the shot assembly with the clamping plate counter bore pocket facing the floor.
25.2. Set the clamping plate on the end cap such that the clamping plate counter bore seats around the end cap (ensuring positive engagement of the two features). NOTE: carefully spin the clamping plate in place to confirm proper/solid seating.

Optional: Two fastener can be screwed in place (fixing the vent side clamping plate to the vent end cap) to ensure that the clamping plate cannot fall during heater assembly. If used, do not torque bolts tight as they will need to be removed for later alignment of the allthread holes for ignitor side and vent side clamping plates.

2 HEATER INSTALLATION

26. Refer to diagram for proper spacing of heaters on tube.

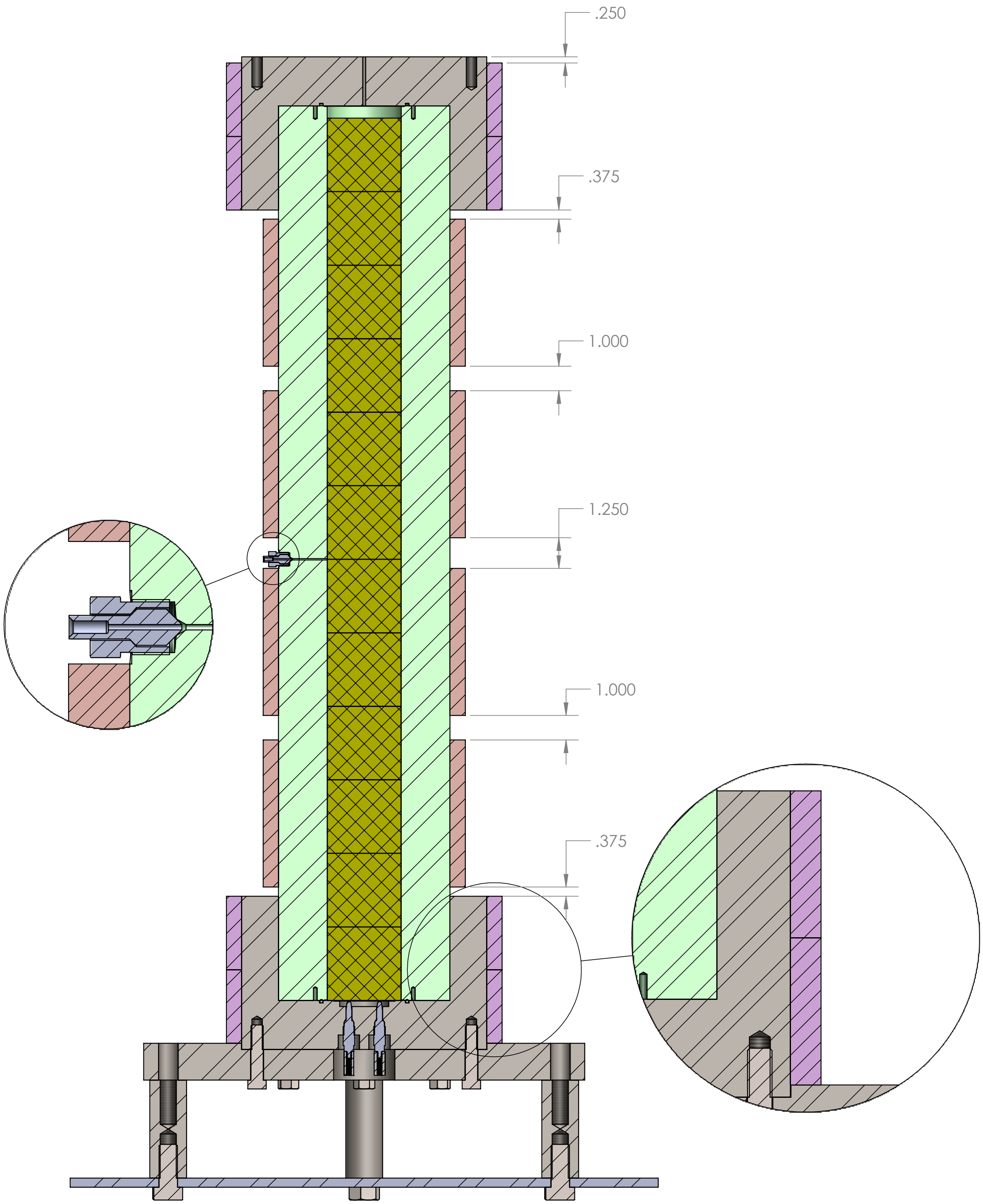


Figure 109. Diagram indicating proper placement of heaters.

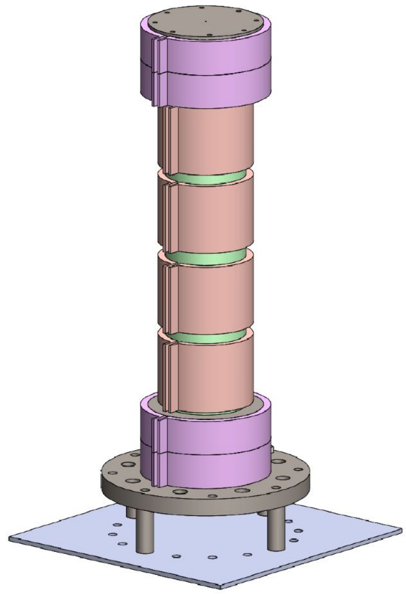


Figure 110. Depiction of shot with heaters installed.

Figure 111. Photograph of heaters installed.

27. Wire up heaters with expendable cables.
28. Mount exterior thermocouples.
    28.1. Each exterior thermocouple is taped to the side of the steel tube.
    28.2. Install exterior TCs in the positions seen in Figure 112 and with the different material layers as seen in Figure 113. Note: the pieces used to cover the external TCs should be of practical size to cover the TC probe, allowing proper adhesion to the steel tube and to provide a practical and sufficient amount of insulation to protect from environmental effects (e.g. cold wind blowing on the TC probe tip). The steel flashing should be large enough in width and length as to be captured and held in place by the heater bands.

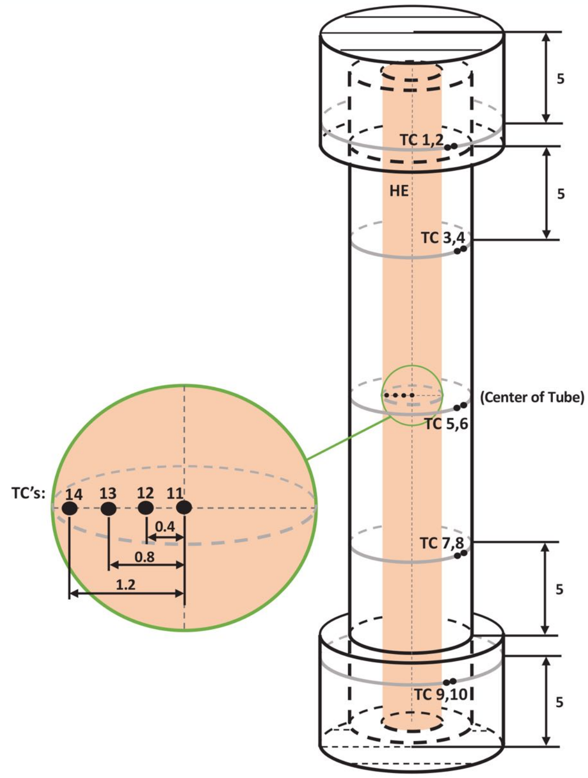


Figure 112: TC Location (Vent end on top of tube).

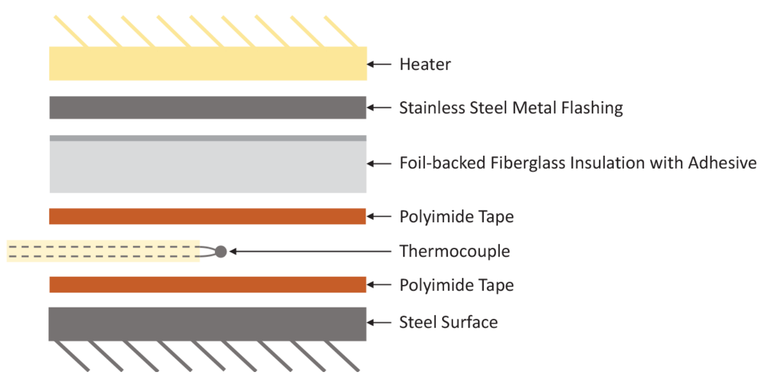


Figure 113: Material layers for installing thermocouples

29. Installing threaded rod. Note: This process can be modified (as it may be necessary) if the interior space in the block house does not permit the manipulation of the threaded rods inside the block house. Procedures used to FY 20 and 21 to complete this operation differed slightly.
    29.1. Option 1 (similar to as used in FY21):
        29.1.1. 2 personnel minimum carefully remove the vent end clamping plate (this may not be necessary if the clamping plate was not installed earlier in section 25.
        29.1.2. Make sure all 8 allthread rod sections are to size/length and have a generous chamfer on one end of the rod and a de-burred flat end on the other.

29.1.3. Insert the flat end of the threaded rod into its corresponding hole in the igniter end clamping plate (repeat for remaining 7 holes).
29.1.4. Install an appropriate plain washer, lock washer, and nut to the section of rod underneath the bottom clamping plate.
29.1.5. 2 personnel minimum lift the vent end clamping plate (with the counterbore facing down) over top the vent end cap.
29.1.6. The 2 personnel slowly lower the clamping plate while a third worker aligns the individual allthread rods into the corresponding hole in the vent end clamping plate until the counterbore of the clamping plate seats on the endcap. NOTE: be mindful of and avoid pinching/crushing while lowering plate and aligning allthread.
29.1.7. Install the same appropriate plain washer, lock washer, and nut to the section of allthread sticking above the clamping plate surface.
29.1.8. Torque threaded rod assembly in star pattern, working back and forth to maintain the clamping plate level: final torque should be 40-45 ft-lbs on each rod assembly. Ensure that all split lock washers are completely flattened.

29.2. Proposed alternative Option 2 for installing allthread.
29.3. 2 personnel minimum carefully remove the vent end clamping plate (this may not be necessary if the clamping plate was not installed earlier in section 25.
29.4. Make sure all 8 allthread rod sections are to size/length and have a generous chamfer on one end of the rod and a de-burred flat end on the other.
29.5. Firmly attach a steel 2-piece split-shaft-collar to each all thread rod ~3.75 inches from the flat end of the rod (measured from the shaft collar side closest to the flat end of the rod (see Figure 114)).

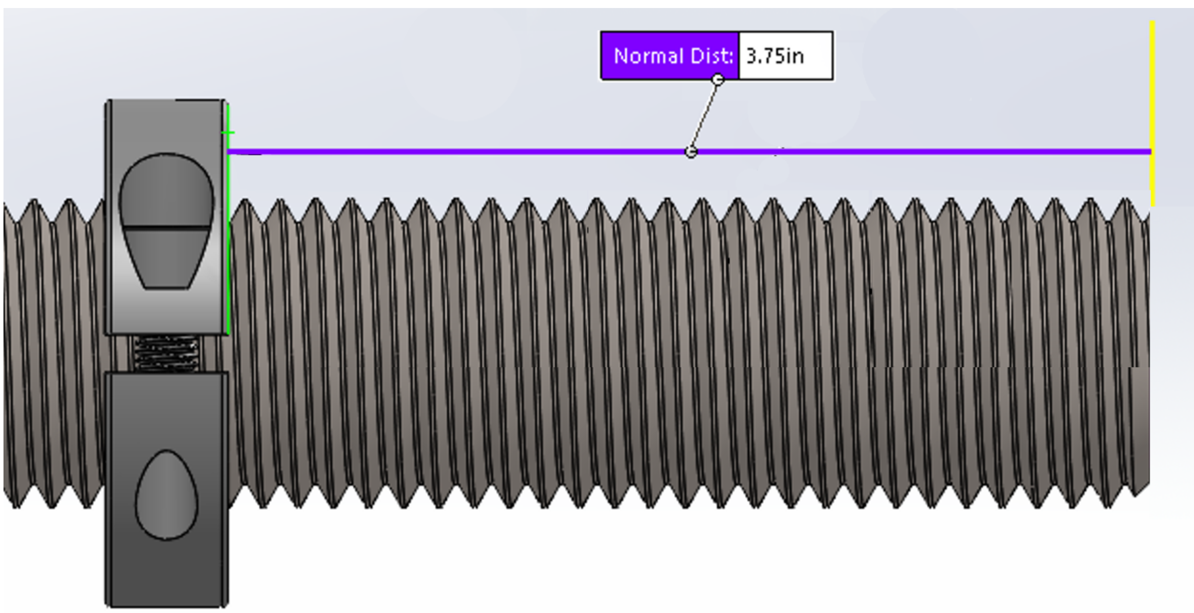


Figure 114: Standoff distance of shaft collar to flat end of allthread

29.6. Insert the flat end of the allthread (threaded rod) into its respective hole in the bottom clamping plate so the chamfered end of the rod is sticking up near the vent end of experiment.
29.7. Install the appropriate plain washer, and lock washer, and nut to the length of allthread sticking below the igniter end clamping plate and hand tighten so the shaft collar is held flat to the clamping plate (allthread should be sticking straight upward).
29.8. Repeat for all remaining 7 threaded rods.
29.9. 2 workers minimum lift the vent end clamping plate up and over chamfered end of the threaded rods with the counterbore facing downward.
29.10. Navigate the threaded rods into the respective holes in the clamping plate; lowering the clamping plate until it rests on the vent end cap. NOTE: Be careful to avoid pinch/crush hazard.
29.11. Install the appropriate plain washer, lock washer, and nut to the length of allthread sticking above the vent end clamping plate. Repeat for seven remaining threaded rods and hand tighten.
29.12. Remove all shaft collars from the threaded rods
29.13. Torque threaded rod assembly in star pattern, working back and forth to maintain the clamping plate level; final torque should be 40-45 ft-lbs. Ensure that all split lock washers are completely flattened.

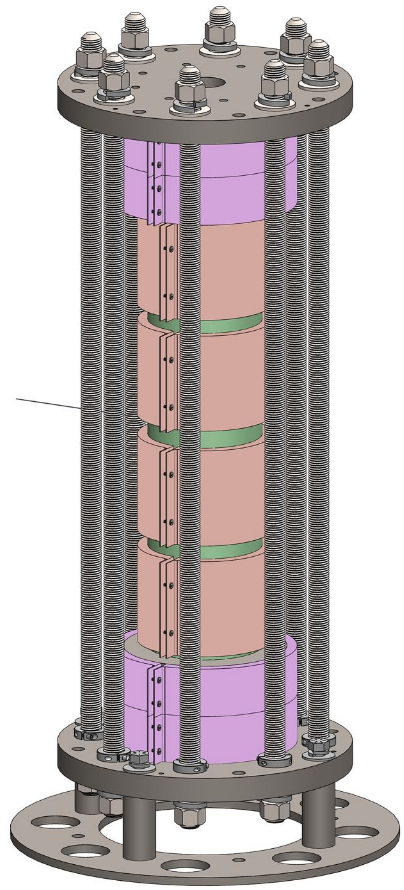


Figure 115. Remainder of threaded rods installed (shaft collars not removed yet).

3 FINAL MECHANICAL ASSEMBLY AND TORQUING

30. Installing the top blast shield.
    30.1. Using the following hardware: ¾-10 UNC X2.25 inch, split lock washer, and plain washer; fasten 4 X steel standoffs (at positions of 0, 90, 180, and 270 degrees) to the top of the vent side clamping plate. Torque to 40-45 ft-lbs.

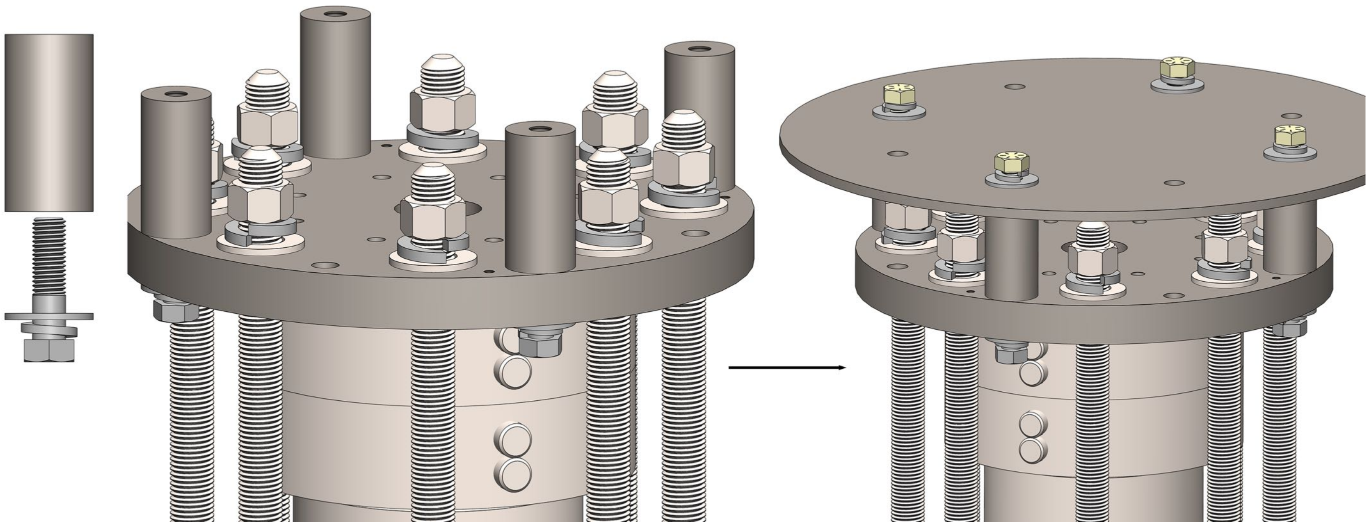


Figure 116 Installing vent side blast shield

30.2. Place vent side blast shield on top of the standoffs and use ¾-10 UNC X2.25 inch, split washer, and plain washer to fasten the blast shield to the standoffs. Torque to 40-45 ft-lbs.

31. Installing the bottom blast shield
    31.1. Fasten one of the two retaining plates to the bottom blast shield using 2X: ¼-20 UNC X .875" SHCS, split lock washer, and plain washers.

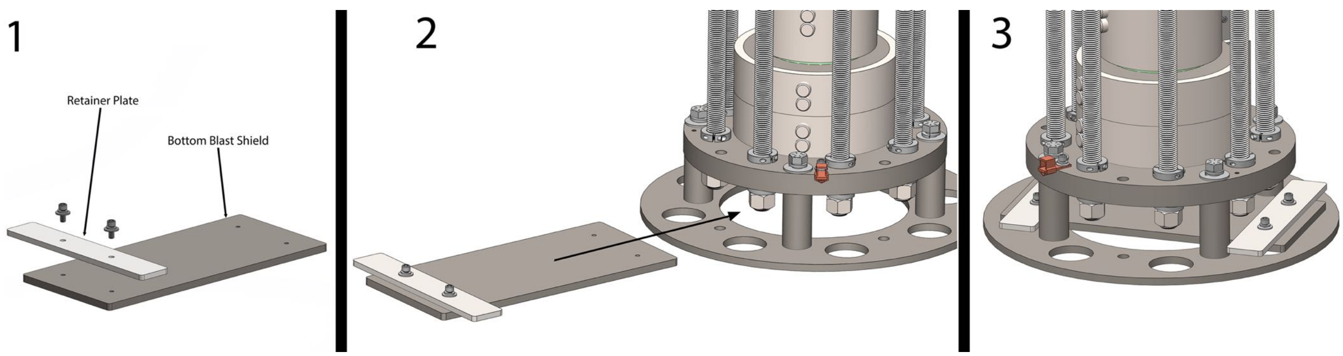


Figure 117 Installation of the bottom blast shield.

31.2. Slide the partially assembled bottom blast shield between the bottom plate and the clamping plate (as seen in Figure 117).
31.3. Fasten the final retainer plate as described in section 31.1.

4 SET UP DIAGNOSTICS & CONTROL EQUIPMENT

32. Using plug locks and/or bags, establish plug control of the following cable plugs in the bunker:
    32.1. Heater power
    32.2. Glow plug power
    32.3. Thermocouple DAQ power (if using internal thermocouples)
33. For above items, mark both ends of any cables with red tape.
34. DOUBLE CHECK that the ends are correct on both sides; the glow plug power MUST NOT be accidentally plugged into any power supply.
35. Provide the keys to firing leader to establish control
36. After verifying firing leader control of keys, make the following connections on the firing mound:
    36.1. Wire heaters on the point to the power cables
    36.2. Wire glow plugs on the point to power cables
    36.3. Plug thermocouples into extension cables
37. Mount/Install PDV probes (if being utilized)
    37.1. Perform alignment operations using eye-safe red guide laser.

37.2. Clear the mound and establish laser hazard clearance when necessary for the purpose of checking laser power returns.
38. Run cabling and make connections for piezo-pin trigger.
39. Set up high-speed video diagnostics.
 39.1. Mount turning mirrors.
 39.2. Align and focus camera.
 39.3. Establish and record camera settings.
40. Install work lights for night-time visibility in and around block house.
41. Install continuous lighting for high-speed videography
42. Set up surveillance camera in blockhouse.
43. Perform trigger test
 43.1. Arm the following equipment:
  43.1.1. Scope armed
  43.1.2. SRS in External trigger mode
  43.1.3. PDV scope(s) armed
  43.1.4. High-speed video armed
 43.2. Tap-test piezo pin, checking that all equipment triggered

5 TEST EXECUTION

44. Check phantom camera framing and focus.
45. Check that the following cable plug ends are safed with plug locks/bags:
  45.1.1. Thermocouple cable plugs in bunker.
  45.1.2. Glow plug cable plug(s).
  45.1.3. All heater cable plugs.
46. Remote control operator checks proper connections and operation of all equipment from remote location while local personnel standby.
 46.1. All surveillance cameras operational
 46.2. Ability to operate devices on the relay box, including:
  46.2.1. Siren
  46.2.2. Work lights
  46.2.3. Lighting for high-speed video
 46.3. Ability to turn on power to glow-plug-power-supply via NI chassis using MAX
 46.4. Ability to control power supply over remote desktop (DO NOT TURN ON GLOW PLUGS!!)
 46.5. Remote desktop control of main oscilloscope
 46.6. Remote control of PDV equipment
  46.6.1. Remote control of PDV oscilloscope(s) using VISA software
  46.6.2. Remote control of Polatis switch (if using)
  46.6.3. Remote control of Luna (if using)
 46.7. Remote access/control of Phantom camera (confirm trigger settings are correct)
47. Remote operator confirms to local personnel that software controlling heaters and glow plug are in the off state prior to final electrical connections.
48. Local personnel make final electrical connections.
 48.1. Insert thermocouple DAQ modules into chassis
 48.2. Connect heater power leads plugs into relay boxes (matching proper numbers).
 48.3. Plug the glow-plug-power-supply-plug into relay box.
49. Local personnel retreat to bunker for final tests.
50. Local personnel insert PDV laser interlock key and power up laser to emission.
51. Remote operator tests **heater power** with brief small application of power.
52. PRIOR TO DEPARTING FIRING SITE:
 52.1. Ensure that SRS is in External trigger mode.
 52.2. Ensure that lighting in bunker(s) is appropriate for remote surveillance cameras
 52.3. Ensure that PDV laser is powered on and emitting (if applicable)

Appendix I Assembly procedure – Intentional Detonation

Assembly Procedure
IHE Qualification DDT Tube Series
Deliberate Detonation (Prills and Pellets)

EXPERIMENT RECORD
Starting Date: ____
Experiment ID: ____________________________________
Assembly team: ____

NOTES

1. Use figures for component identification. Component names are boldfaced when initially referenced.
2. When ordering items for the full IHE Qualification DDT Test, a 10th full length tube should be ordered and then sectioned to produce the two tubes needed for the intentional detonation test.
3. Print a separate hardcopy of this assembly procedure for each experiment. Check off steps as they are completed and note deviations, difficulties, or modifications to the procedure.

Basic Tool List (additional materials or tools may be needed)
Heavy Duty Chain/Strap
Cotton wipes
Cotton swabs
Cleaning solvent (e.g. ethyl or isopropyl alcohol)
Bore brushes or wire brush
Flexible tape measure
Combination Square and 12 inch scale
4 in. wide Kapton tape
Vacuum grease
Pry bars

Parts List
Machined parts:
- Short Tube
- Vent endcap

Teledyne RISI RP-83 Detonator
Comp-C4 High Explosive
Comp C-4 Booster Form

Figure 118: Post detonation fragment re-construction.

EXPERIMENT ASSEMBLY

1. Prepare short tube assembly
    1.1. Measure and record the total length of the **short tube** (tube length should be ~16.25 inches long).
    1.2. Transport 1X **short tube** and 1X **vent end cap** to the blockhouse via forklift or truck.
    1.3. Clean the bore of the short tube with an appropriate solvent to remove grit and machining oil.
    1.4. Inspect bore for rust or grit. If clean, tape both ends to avoid contaminating with grit during orientation of tube for assembly.
    1.5. Installing **vent end cap** on **short tube.**
        1.5.1. Orient the short tube vertically so that the non-threaded section of the tube is resting on the floor in the blockhouse.
        1.5.2. Use wooden boards or other materials to assemble a temporary support to keep the tube vertical and stable while installing threaded vent end cap as seen in Figure 119 *left*.
        1.5.3. Clean the tube threads and tube face, and apply a small amount of light duty anti-seize to the threads.
        1.5.4. Clean the threads and pocket face of the vent end cap.
        1.5.5. Remove tape on threaded end of the short tube.
        1.5.6. Lift and thread the vent end cap onto the short tube until it fully bottoms out (two counter acting strap/chain wrenches may be needed to complete this step.
        1.5.7. Remove temporary support and carefully lower assembly so it lies horizontal on floor.
        1.5.8. Measure the total distance from the open end of the short tube to the pocket face of the vent end cap, see Figure 119 *right*. Document with a photograph as seen in Figure 119 *right*.

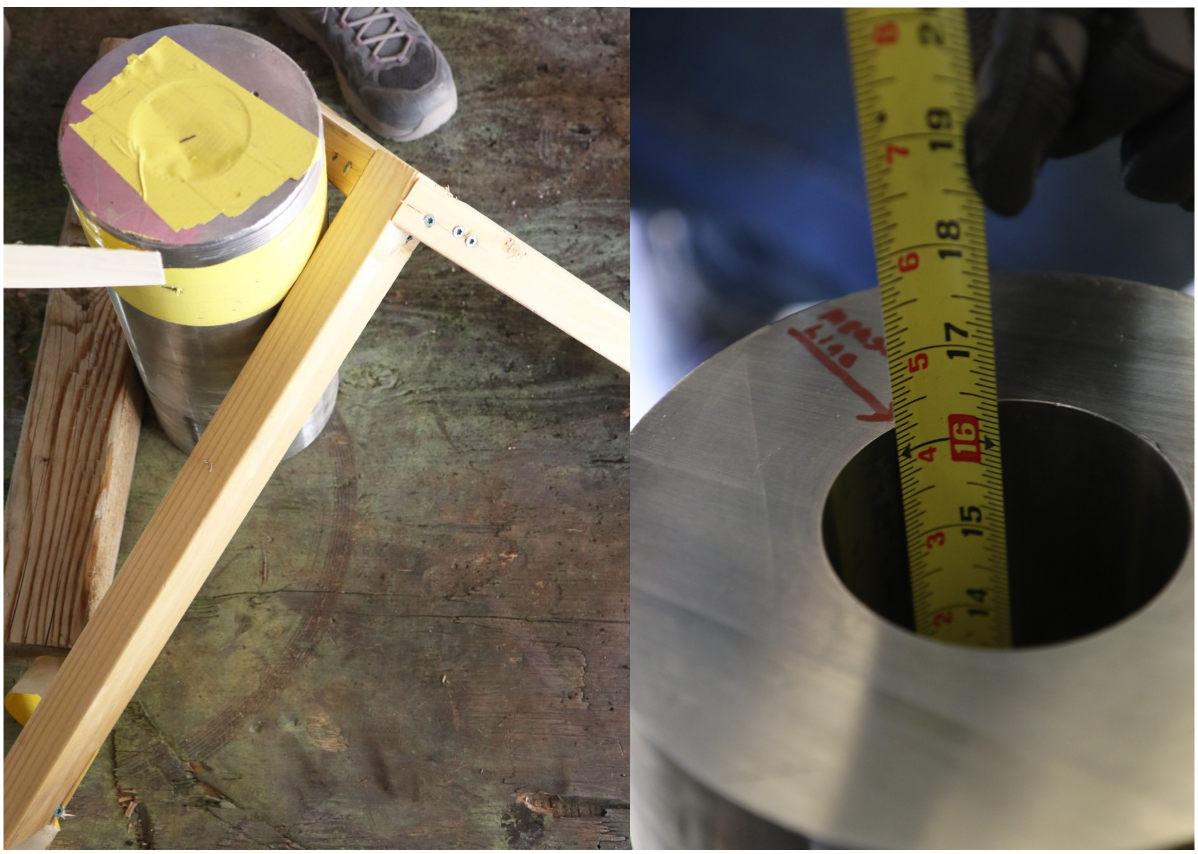


Figure 119: *Left*: short tube oriented for installation of vent end cap (yellow protecting tape seen). *Right*: Measurement of bore depth

2. Forming the Comp-C4 Booster Charge
    2.1. Acquire and clean an appropriate form to make a 3 inch X 3 inch right cylinder booster charge. Note: in FY21 (see Figure 120) the form consisted of a HDPE hollow-right-cylinder with a three inch bore, three inches tall. A PTFE plug is included to push the booster charge out of the form.
        2.1.1. Clean the HDPE form and place on a flat and sturdy table surface.
        2.1.2. Place Comp-C4 material into the inner volume of the form while keeping the form held to the table surface.

2.1.3. Carefully add and compress Comp-C4 into the inner volume of the form, pressing with each addition of material in order to prevent large voids from being included in the booster charge.
2.1.4. Once the material is level with the top of the form, slowly push the Comp-C4 plug of material out of the form using the PTFE plug.
2.1.5. Obtain and record the mass of the booster charge. Visually inspect booster charge for major cracks (that would make charge mechanically unstable).

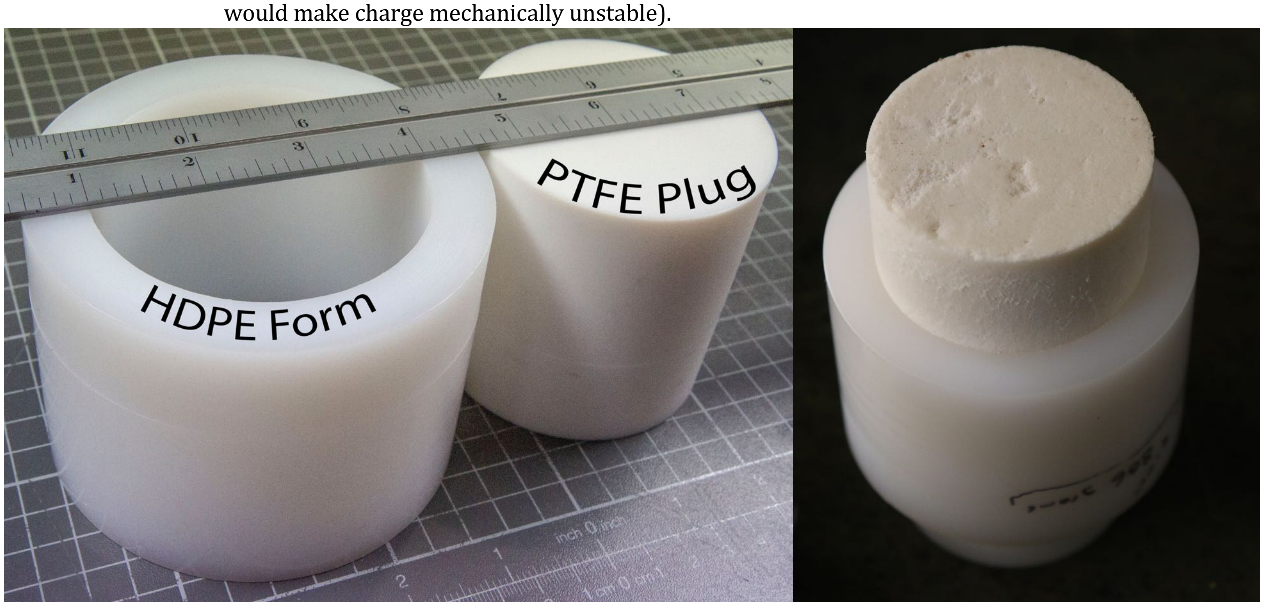


Figure 120: ***Left*****: Form and plug for shaping booster charge.** ***Right*****: Comp-C4 charge halfway pushed out of form.**

3. Filling tube with HE
   3.1. **Consolidated Pressed Pellets**
      3.1.1. Prop the open end of the tube assembly so that there is a slight grade of the bore from the open end to the capped end.
      3.1.2. Measure and record each pressed HE pellet height to be used in the intentional detonation.
      3.1.3. Remove the bore protecting tape and re-inspect the bore for grit.
      3.1.4. By hand, slowly insert and push each pressed pellet of HE into the bore. Start with one, 1X3 inch PBX-9502 pressed pellet; followed by three, 3X3 inch PBX-9502 pellets (see Figure 121 *left*). Note: ensure each pellet is fully pressed up against each other and are pushed up to the bottom pocket in the vent end cap.
      3.1.5. Measure the distance from the top PBX 9502 HE pellet to the open end of the short tube as a sanity check to make sure the pellets are fully seated to the vent end cap.

Figure 121: ***Right*****: Installing a 3"X3" PBX-9502 pressed pellet into tube.** ***Left*****: Installing booster charge.**

      3.1.6. Install the Comp-C4 booster charge similar to how the PBX-9502 charge was inserted. Gently push the booster charge against the top PBX 9502 charge.
      3.1.7. Measure the distance from the open end of the short tube to the face of the booster charge.
      3.1.8. Carefully upright the assembly so that the open end of the tube is at the highest point of the assembly.

3.1.9. Following standard safety procedures for intentional firing operations: install the RP-83 detonator and execute the intentional detonation. Depiction of final assembly seen in Figure 122.

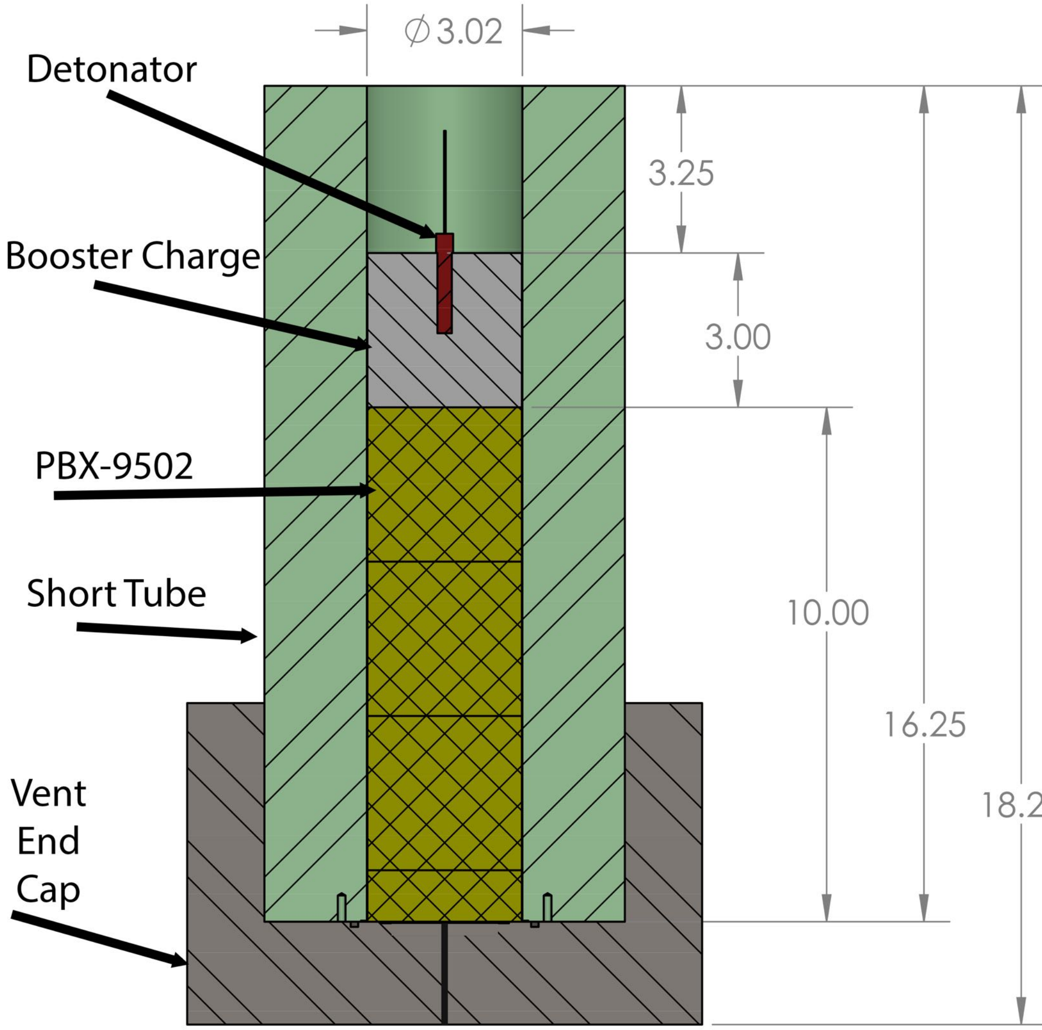


Figure 122: Depiction of intentional detonation assembly

3.1.10. Observe and photograph fragments produced by resulting detonation. Note: it may be useful to have some sort of indicating marks on the tube to help with fragment re-construction as seen in Figure 118 (on the title page). This helps determine what fragments were produced by the detonation of the Comp-C4 and the detonation of the PBX-9502.

3.2. Molding Prills

3.2.1. Upright the tube so that the open end is the highest part of the assembly.

3.2.2. Using an appropriate funnel, pour molding prills into the tube such that the prill HE column is 10 inches tall (at pour density). Be sure to track the mass of HE poured into the tube assembly.

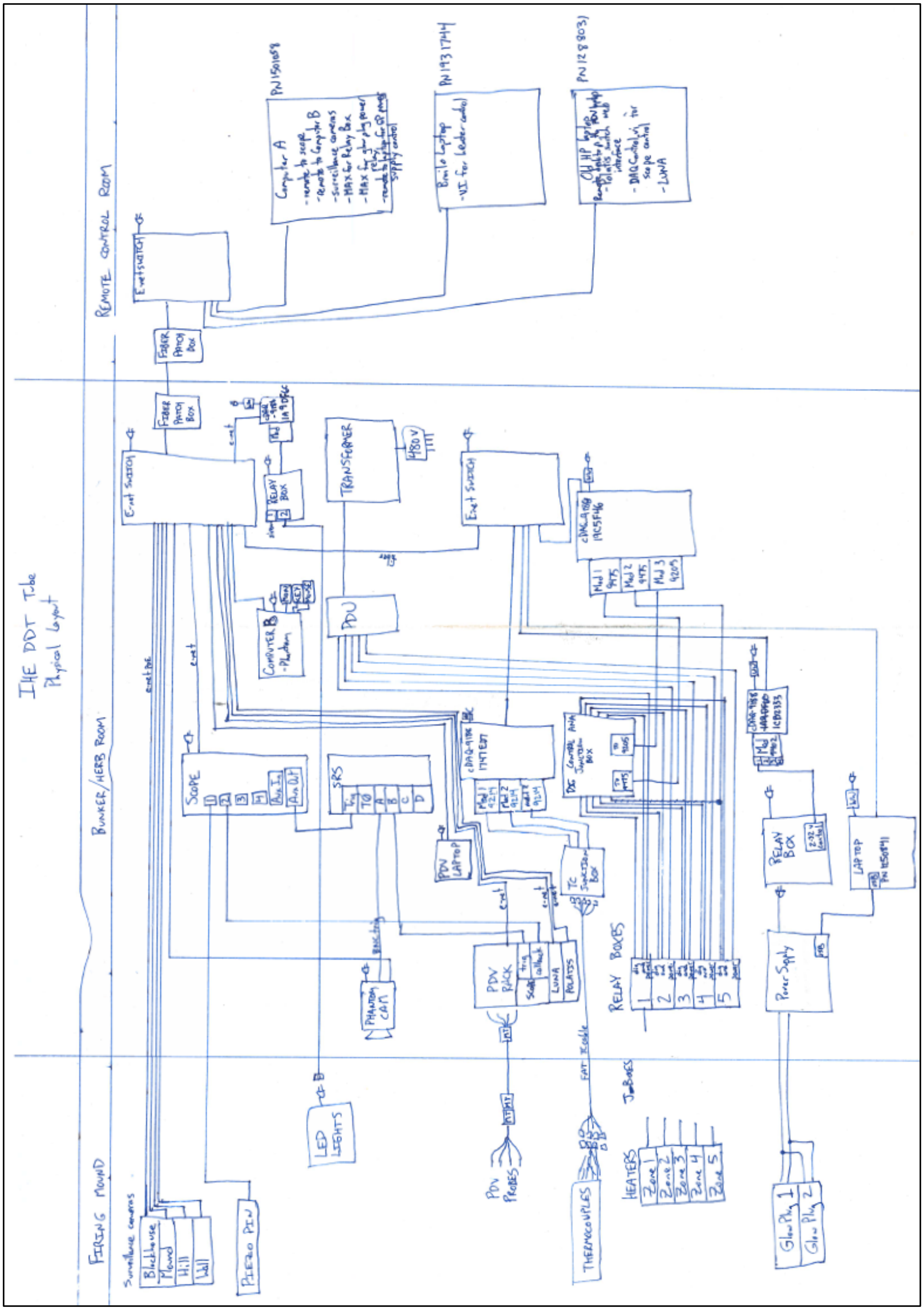
3.2.3. Using a plastic spatula, roughly flatten the top surface of the prill column without compressing it.

3.2.4. Insert the Comp-C4 booster charge by lowering it into the tube. A thin piece(s) of string (e.g. nylon floss) can be used to lower the charge down to the molding prill column (no need to remove string if roughly the size of typical floss). Measure the distance to the top of the booster charge to make sure it is contacting the prill column.

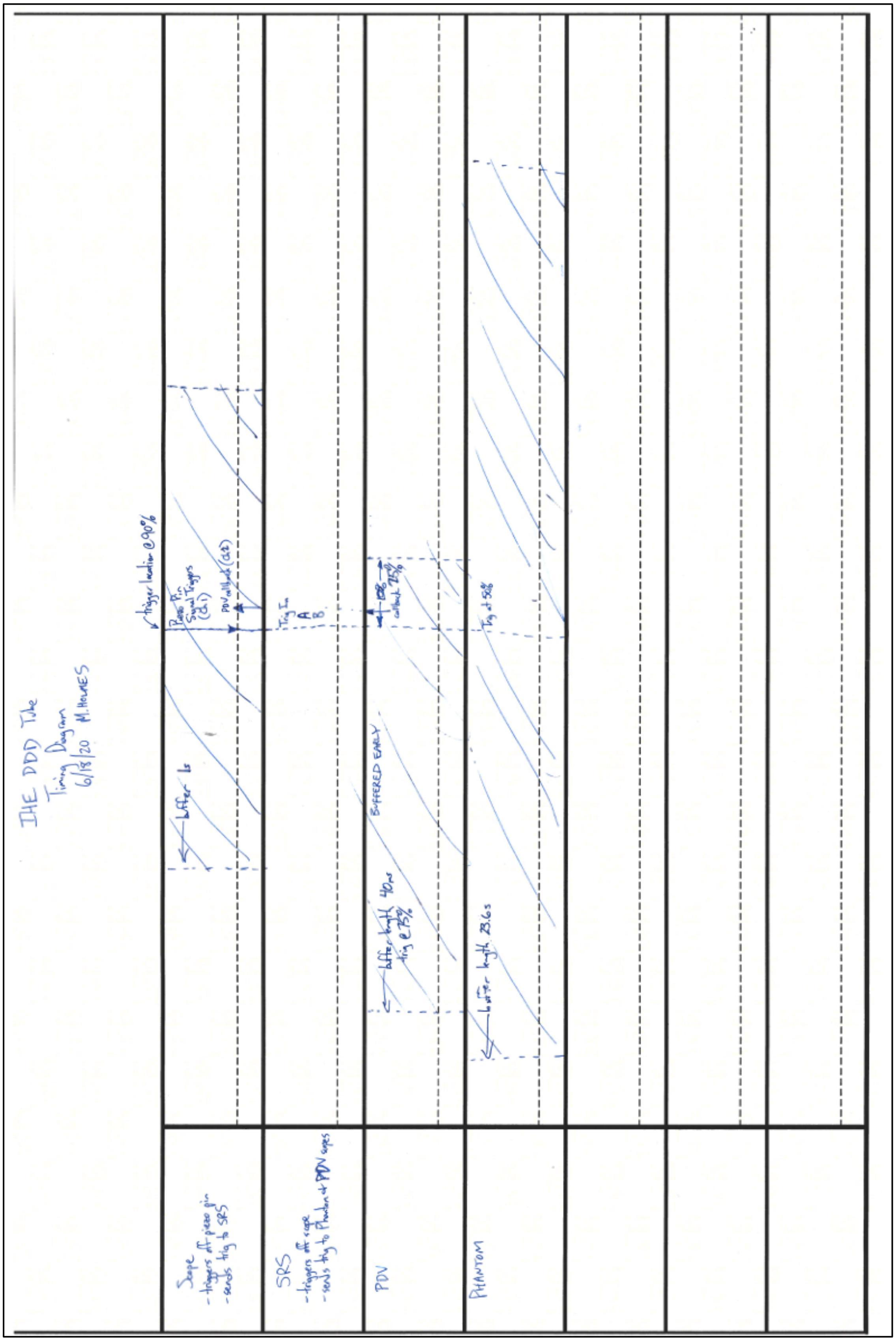
3.2.5. Follow standard procedures for intentional firing operations for installing the RP-83 detonator and firing the shot.

3.2.6. Observe and document resulting fragments.

Appendix J Wiring Diagram



Appendix K Timing Diagram



Appendix L Explosive Machining Reports

3321-02 — 3"x3" cylinders

	Material	Density at 20 °C Temp	Coeff. Thermal Expan.	Dry Weight	Water Temp	Water Density	Wet Weight	Correction based on S density	Density at 20 °C Temp	Height face to face (in)
	Silicon	2.329	7.70E-06	677.523	18.10	0.99858	387.059	1.00034	2.329	
19-176-01	**9502**	1.889	1.50E-04	657.609	18.10	0.99858	310.103	1.00034	1.889	3.013
19-176-02	**9502**	1.890	1.50E-04	656.445	18.10	0.99858	309.803	1.00034	1.890	3.004
19-176-03	**9502**	1.890	1.50E-04	658.502	18.10	0.99858	310.692	1.00034	1.890	3.014
19-176-04	**9502**	1.890	1.50E-04	658.232	18.10	0.99858	310.672	1.00034	1.890	3.012
19-176-05	**9502**	1.887	1.50E-04	657.645	18.10	0.99858	309.778	1.00034	1.887	3.016
19-176-06	**9502**	1.890	1.50E-04	658.451	18.10	0.99858	310.734	1.00034	1.890	3.014
19-176-07	**9502**	1.890	1.50E-04	658.222	18.10	0.99858	310.544	1.00034	1.890	3.013
19-176-08	**9502**	1.889	1.50E-04	658.755	18.10	0.99858	310.645	1.00034	1.889	3.014
19-176-09	**9502**	1.890	1.50E-04	659.002	18.10	0.99858	310.897	1.00034	1.890	3.019
19-176-10	**9502**	1.890	1.50E-04	658.720	18.10	0.99858	310.917	1.00034	1.890	3.013
19-176-11	**9502**	1.889	1.50E-04	658.463	18.10	0.99858	310.539	1.00034	1.889	3.018
19-176-12	**9502**	1.888	1.50E-04	658.470	18.10	0.99858	310.365	1.00034	1.888	3.018
19-176-13	**9502**	1.891	1.50E-04	658.098	18.10	0.99858	310.662	1.00034	1.891	3.018
19-176-14	**9502**	1.891	1.50E-04	659.133	18.10	0.99858	311.142	1.00034	1.891	3.022
19-176-15	**9502**	1.891	1.50E-04	658.339	18.10	0.99858	310.749	1.00034	1.891	3.015
	Silicon	2.329	7.70E-06	677.523	18.30	0.99854	387.086	1.00030	2.329	
19-176-16	**9502**	1.891	1.50E-04	658.115	18.30	0.99854	310.826	1.00030	1.891	3.014
19-176-17	**9502**	1.891	1.50E-04	658.742	18.30	0.99854	310.989	1.00030	1.891	3.016
19-176-18	**9502**	1.890	1.50E-04	658.988	18.30	0.99854	310.936	1.00030	1.890	3.018
19-176-19	**9502**	1.890	1.50E-04	658.497	18.30	0.99854	310.805	1.00030	1.890	3.014
19-176-20	**9502**	1.891	1.50E-04	658.525	18.30	0.99854	310.996	1.00030	1.891	3.014
19-176-21	**9502**	1.890	1.50E-04	659.067	18.30	0.99854	310.983	1.00030	1.890	3.020
19-176-22	**9502**	1.891	1.50E-04	658.945	18.30	0.99854	311.046	1.00030	1.891	3.017
19-176-23	**9502**	1.891	1.50E-04	658.631	18.30	0.99854	310.964	1.00030	1.891	3.015
19-176-24	**9502**	1.891	1.50E-04	658.513	18.30	0.99854	310.945	1.00030	1.891	3.015
19-176-25	**9502**	1.890	1.50E-04	664.574	18.30	0.99854	313.662	1.00030	1.890	3.042
19-176-26	**9502**	1.890	1.50E-04	664.496	18.30	0.99854	313.531	1.00030	1.890	3.042
19-176-27	**9502**	1.891	1.50E-04	658.516	18.30	0.99854	310.982	1.00030	1.891	3.012
19-176-28	**9502**	1.890	1.50E-04	658.843	18.30	0.99854	310.915	1.00030	1.890	3.014

19-176-29	**9502**	1.890	1.50E-04	658.973	18.30	0.99854	310.933	1.00030	1.890	3.015
19-176-30	**9502**	1.890	1.50E-04	658.458	18.30	0.99854	310.794	1.00030	1.890	3.014
	Silicon	2.329	7.70E-06	677.520	17.80	0.99863	387.088	1.00023	2.329	
19-176-31	**9502**	1.890	1.50E-04	658.857	17.80	0.99863	310.915	1.00023	1.890	3.016
19-176-32	**9502**	1.891	1.50E-04	658.823	17.80	0.99863	311.036	1.00023	1.891	3.014
19-176-33	**9502**	1.890	1.50E-04	658.708	17.80	0.99863	310.935	1.00023	1.890	3.011
19-176-34	**9502**	1.890	1.50E-04	658.735	17.80	0.99863	310.909	1.00023	1.890	3.012
19-176-35	**9502**	1.891	1.50E-04	658.470	17.80	0.99863	310.878	1.00023	1.891	3.011
19-176-36	**9502**	1.892	1.50E-04	658.626	17.80	0.99863	311.123	1.00023	1.892	3.011
19-176-37	**9502**	1.892	1.50E-04	658.376	17.80	0.99863	311.032	1.00023	1.892	3.008
19-176-38	**9502**	1.892	1.50E-04	658.728	17.80	0.99863	311.202	1.00023	1.892	3.009
19-176-39	**9502**	1.892	1.50E-04	658.325	17.80	0.99863	311.033	1.00023	1.892	3.009
19-176-40	**9502**	1.892	1.50E-04	658.258	17.80	0.99863	311.094	1.00023	1.892	3.007
19-176-41	**9502**	1.892	1.50E-04	658.635	17.80	0.99863	311.156	1.00023	1.892	3.010
19-176-42	**9502**	1.892	1.50E-04	658.826	17.80	0.99863	311.194	1.00023	1.892	3.014
19-176-43	**9502**	1.891	1.50E-04	658.571	17.80	0.99863	311.035	1.00023	1.891	3.014
19-176-44	**9502**	1.892	1.50E-04	658.821	17.80	0.99863	311.246	1.00023	1.892	3.015
19-176-45	**9502**	1.892	1.50E-04	658.158	17.80	0.99863	310.874	1.00023	1.892	3.013
	Silicon	2.329	7.70E-06	677.520	18.00	0.99860	387.097	1.00023	2.329	
19-176-46	**9502**	1.891	1.50E-04	658.185	18.00	0.99860	310.818	1.00023	1.891	3.010
19-176-47	**9502**	1.891	1.50E-04	658.918	18.00	0.99860	311.188	1.00023	1.891	3.013
19-176-48	**9502**	1.892	1.50E-04	658.872	18.00	0.99860	311.365	1.00023	1.892	3.010
19-176-49	**9502**	1.892	1.50E-04	658.591	18.00	0.99860	311.220	1.00023	1.892	3.009
19-176-50	**9502**	1.892	1.50E-04	658.472	18.00	0.99860	311.170	1.00023	1.892	3.009
19-176-51	**9502**	1.892	1.50E-04	658.187	18.00	0.99860	310.976	1.00023	1.892	3.008
19-176-52	**9502**	1.892	1.50E-04	659.063	18.00	0.99860	311.388	1.00023	1.892	3.012
19-176-53	**9502**	1.892	1.50E-04	658.772	18.00	0.99860	311.208	1.00023	1.892	3.011
19-176-54	**9502**	1.892	1.50E-04	658.408	18.00	0.99860	311.005	1.00023	1.892	3.009
19-176-55	**9502**	1.892	1.50E-04	658.727	18.00	0.99860	311.184	1.00023	1.892	3.012
19-176-56	**9502**	1.892	1.50E-04	658.876	18.00	0.99860	311.246	1.00023	1.892	3.012
19-176-57	**9502**	1.892	1.50E-04	658.533	18.00	0.99860	311.166	1.00023	1.892	3.008
19-176-58	**9502**	1.892	1.50E-04	658.164	18.00	0.99860	310.933	1.00023	1.892	3.010
19-176-59	**9502**	1.891	1.50E-04	658.396	18.00	0.99860	310.922	1.00023	1.891	3.011
19-176-60	**9502**	1.891	1.50E-04	658.794	18.00	0.99860	311.069	1.00023	1.891	3.012
	Silicon	2.329	7.70E-06	677.513	17.40	0.99871	387.045	1.00027	2.329	

19-176-61	**9502**	1.892	1.50E-04	658.759	17.40	0.99871	311.188	1.00027	1.892	3.010
19-176-62	**9502**	1.891	1.50E-04	658.700	17.40	0.99871	311.059	1.00027	1.891	3.009
19-176-63	**9502**	1.892	1.50E-04	658.613	17.40	0.99871	311.078	1.00027	1.892	3.010
19-176-64	**9502**	1.892	1.50E-04	657.590	17.40	0.99871	310.655	1.00027	1.892	3.004
19-176-65	**9502**	1.892	1.50E-04	657.869	17.40	0.99871	310.725	1.00027	1.892	3.009
19-176-66	**9502**	1.892	1.50E-04	658.238	17.40	0.99871	310.904	1.00027	1.892	3.009
19-176-67	**9502**	1.891	1.50E-04	658.969	17.40	0.99871	311.213	1.00027	1.891	3.010
19-176-68	**9502**	1.892	1.50E-04	658.635	17.40	0.99871	311.108	1.00027	1.892	3.009
19-176-69	**9502**	1.892	1.50E-04	658.730	17.40	0.99871	311.186	1.00027	1.892	3.010
19-176-70	**9502**	1.892	1.50E-04	657.798	17.40	0.99871	310.805	1.00027	1.892	3.005
19-176-71	**9502**	1.891	1.50E-04	658.398	17.40	0.99871	310.844	1.00027	1.891	3.009
19-176-72	**9502**	1.891	1.50E-04	658.542	17.40	0.99871	311.025	1.00027	1.891	3.009
19-176-73	**9502**	1.892	1.50E-04	658.229	17.40	0.99871	311.039	1.00027	1.892	3.006
19-176-74	**9502**	1.892	1.50E-04	658.748	17.40	0.99871	311.238	1.00027	1.892	3.008
19-176-75	**9502**	1.892	1.50E-04	658.744	17.40	0.99871	311.208	1.00027	1.892	3.009
	Silicon	2.329	7.70E-06	677.514	17.30	0.99872	387.041	1.00027	2.329	
19-176-76	**9502**	1.890	1.50E-04	658.801	17.30	0.99872	310.962	1.00027	1.890	3.010
19-176-77	**9502**	1.891	1.50E-04	658.661	17.30	0.99872	311.065	1.00027	1.891	3.009
19-176-78	**9502**	1.891	1.50E-04	658.321	17.30	0.99872	310.921	1.00027	1.891	3.010
19-176-79	**9502**	1.892	1.50E-04	658.439	17.30	0.99872	311.036	1.00027	1.892	3.004
19-176-80	**9502**	1.892	1.50E-04	658.729	17.30	0.99872	311.125	1.00027	1.892	3.009
19-176-81	**9502**	1.892	1.50E-04	657.841	17.30	0.99872	310.740	1.00027	1.892	3.009
19-176-82	**9502**	1.892	1.50E-04	658.531	17.30	0.99872	311.037	1.00027	1.892	3.010
19-176-83	**9502**	1.892	1.50E-04	658.608	17.30	0.99872	311.162	1.00027	1.892	3.009
19-176-84	**9502**	1.892	1.50E-04	658.421	17.30	0.99872	311.031	1.00027	1.892	3.010
19-176-85	**9502**	1.891	1.50E-04	658.475	17.30	0.99872	311.001	1.00027	1.891	3.005
19-176-86	**9502**	1.892	1.50E-04	658.632	17.30	0.99872	311.128	1.00027	1.892	3.009
19-176-87	**9502**	1.892	1.50E-04	658.415	17.30	0.99872	311.134	1.00027	1.892	3.009
19-176-88	**9502**	1.892	1.50E-04	658.408	17.30	0.99872	311.117	1.00027	1.892	3.006
19-176-89	**9502**	1.890	1.50E-04	658.917	17.30	0.99872	310.847	1.00027	1.890	3.008
19-176-90	**9502**	1.892	1.50E-04	656.557	17.30	0.99872	310.137	1.00027	1.892	3.009
	Silicon	2.329	7.70E-06	677.521	19.30	0.99835	387.166	1.00023	2.329	
19-176-91	**9502**	1.891	1.50E-04	658.493	19.30	0.99835	310.955	1.00027	1.891	3.010
19-176-92	**9502**	1.891	1.50E-04	658.491	19.30	0.99835	310.957	1.00027	1.891	3.010
19-176-93	**9502**	1.891	1.50E-04	658.465	19.30	0.99835	311.008	1.00027	1.891	3.010

19-176-94	**9502**	1.892	1.50E-04	658.377	19.30	0.99835	311.060	1.00027	1.892	3.009
19-176-95	**9502**	1.892	1.50E-04	658.421	19.30	0.99835	311.037	1.00027	1.892	3.010
19-176-96	**9502**	1.891	1.50E-04	658.341	19.30	0.99835	310.886	1.00027	1.891	3.010
19-176-97	**9502**	1.892	1.50E-04	658.483	19.30	0.99835	311.033	1.00027	1.892	3.007
19-176-98	**9502**	1.892	1.50E-04	658.489	19.30	0.99835	311.101	1.00027	1.892	3.007
19-176-99	**9502**	1.892	1.50E-04	658.729	19.30	0.99835	311.209	1.00027	1.892	3.010
19-176-100	**9502**	1.891	1.50E-04	658.866	19.30	0.99835	311.196	1.00027	1.891	3.010
19-176-101	**9502**	1.891	1.50E-04	658.239	19.30	0.99835	310.902	1.00027	1.891	3.009
19-176-102	**9502**	1.892	1.50E-04	658.457	19.30	0.99835	311.071	1.00027	1.892	3.010
19-176-103	**9502**	1.891	1.50E-04	658.590	19.30	0.99835	311.065	1.00027	1.891	3.012
19-176-104	**9502**	1.892	1.50E-04	658.999	19.30	0.99835	311.291	1.00027	1.892	3.012
19-176-105	**9502**	1.891	1.50E-04	658.926	19.30	0.99835	311.225	1.00027	1.891	3.012
	Silicon	2.329	7.70E-06	677.521	19.50	0.99831	387.161	1.00027	2.32905	
19-176-106	**9502**	1.892	1.50E-04	658.512	19.50	0.99831	311.119	1.00027	1.892	3.012
19-176-107	**9502**	1.891	1.50E-04	658.646	19.50	0.99831	310.975	1.00027	1.891	3.011
19-176-108	**9502**	1.891	1.50E-04	658.826	19.50	0.99831	311.155	1.00027	1.891	3.011
19-176-109	**9502**	1.892	1.50E-04	658.551	19.50	0.99831	311.099	1.00027	1.892	3.009
19-176-110	**9502**	1.891	1.50E-04	658.467	19.50	0.99831	310.867	1.00027	1.891	3.010
19-176-111	**9502**	1.891	1.50E-04	658.298	19.50	0.99831	310.850	1.00027	1.891	3.009
19-176-112	**9502**	1.892	1.50E-04	658.437	19.50	0.99831	311.189	1.00027	1.892	3.007
19-176-113	**9502**	1.892	1.50E-04	658.809	19.50	0.99831	311.245	1.00027	1.892	3.013
19-176-114	**9502**	1.892	1.50E-04	658.267	19.50	0.99831	311.010	1.00027	1.892	3.009
19-176-115	**9502**	1.891	1.50E-04	658.621	19.50	0.99831	310.952	1.00027	1.891	3.012
19-176-116	**9502**	1.891	1.50E-04	658.591	19.50	0.99831	311.073	1.00027	1.891	3.012
19-176-117	**9502**	1.891	1.50E-04	658.627	19.50	0.99831	311.062	1.00027	1.891	3.011
19-176-118	**9502**	1.891	1.50E-04	657.768	19.50	0.99831	310.679	1.00027	1.891	3.007
19-176-119	**9502**	1.891	1.50E-04	658.452	19.50	0.99831	310.941	1.00027	1.891	3.010
19-176-120	**9502**	1.891	1.50E-04	658.403	19.50	0.99831	310.959	1.00027	1.891	3.010
	Silicon	2.328	7.70E-06	677.514	19.50	0.99831	387.041	1.00027	2.328	
19-176-121	**9502**	1.892	1.50E-04	658.438	19.50	0.99831	311.131	1.00027	1.892	3.009
19-176-122	**9502**	1.892	1.50E-04	658.670	19.50	0.99831	311.157	1.00027	1.892	3.011
19-176-123	**9502**	1.891	1.50E-04	658.720	19.50	0.99831	311.038	1.00027	1.891	3.012
19-176-124	**9502**	1.891	1.50E-04	658.423	19.50	0.99831	310.855	1.00027	1.891	3.009
19-176-125	**9502**	1.891	1.50E-04	658.691	19.50	0.99831	310.982	1.00027	1.891	3.011
19-176-126	**9502**	1.890	1.50E-04	658.413	19.50	0.99831	310.773	1.00027	1.890	3.009

19-176-127	**9502**	1.891	1.50E-04	658.178	19.50	0.99831	310.773	1.00027	1.891	3.008
19-176-128	**9502**	1.891	1.50E-04	657.432	19.50	0.99831	310.490	1.00027	1.891	3.005
19-176-129	**9502**	1.891	1.50E-04	658.260	19.50	0.99831	310.926	1.00027	1.891	3.007
19-176-130	**9502**	1.891	1.50E-04	658.475	19.50	0.99831	311.031	1.00027	1.891	3.009

					3321-01		3"x1" cylinders			
	Material	**Density at 20 °C Temp**	**Coeff. Thermal Expan.**	**Dry Weight**	**Water Temp**	**Water Density**	**Wet Weight**	**Correction based on S density**	**Density at 20 °C Temp**	Height face to face (in)
	Silicon	2.329	7.70E-06	202.544	19.50	0.99831	115.742	1.00027	2.32907	
19-196-01	**9502**	1.889	1.50E-04	219.314	19.50	0.99831	103.467	1.00027	1.889	1.005
19-196-02	**9502**	1.888	1.50E-04	219.332	19.50	0.99831	103.416	1.00027	1.888	1.005
19-196-03	**9502**	1.890	1.50E-04	219.131	19.50	0.99831	103.405	1.00027	1.890	1.005
19-196-04	**9502**	1.890	1.50E-04	219.321	19.50	0.99831	103.507	1.00027	1.890	1.006
19-196-05	**9502**	1.889	1.50E-04	219.245	19.50	0.99831	103.431	1.00027	1.889	1.004
19-196-06	**9502**	1.890	1.50E-04	219.320	19.50	0.99831	103.513	1.00027	1.890	1.010
19-196-07	**9502**	1.889	1.50E-04	219.098	19.50	0.99831	103.352	1.00027	1.889	1.008
19-196-08	**9502**	1.889	1.50E-04	219.438	19.50	0.99831	103.523	1.00027	1.889	1.001
19-196-09	**9502**	1.889	1.50E-04	219.304	19.50	0.99831	103.406	1.00027	1.889	1.009
19-196-10	**9502**	1.890	1.50E-04	219.237	19.50	0.99831	103.450	1.00027	1.890	1.008

Appendix M Heaters

CHROMALOX
Advanced Thermal Technologies

CHROMALOX SALES OFFICE-DENVER (25)
103 Gamma Drive
Pittsburgh, PA 15238 United States
Phone: 866-853-4437
Fax: 412-967-5148
Email: Denver@chromalox.com

November 25, 2019

Matt Holmes
LOS ALAMOS NAT LAB
PO BOX 1663
E536
LOS ALAMOS, NM 87545 USA
Email: mholmes@lanl.gov
505-665-4107

Quote #: 398052 - 00
Valid Until 12/25/2019

Subject: Ceramic Band Heaters

	Part #	Description	Qty.	Unit Price	Ext. Price
1	161090	CB7A6A1P2 240V 5000W	36	238.00 USD	8,568.00 USD
	Manufacturing Lead Time: 17 business days **FOB Shipping Point: LAREDO**				
2	161808	CB10A3A1P1 240V 2400W	36	194.00 USD	6,984.00 USD
	Manufacturing Lead Time: 17 business days **FOB Shipping Point: LAREDO**				
				Materials Total:	15,552.00
				Ungrouped Total (USD):	**15,552.00**

Note: When applicable, quoted approval drawing lead time starts upon receipt of approved credit and is not inclusive of customer review time. Quoted manufacturing lead time begins when the part is engineered and upon receipt of approved credit and/or drawing approval. Shipping time is not included. All drawings supplied will be in PDF format only.

Comments

Net pricing does not include freight. Please reference quote 398052 when ordering.

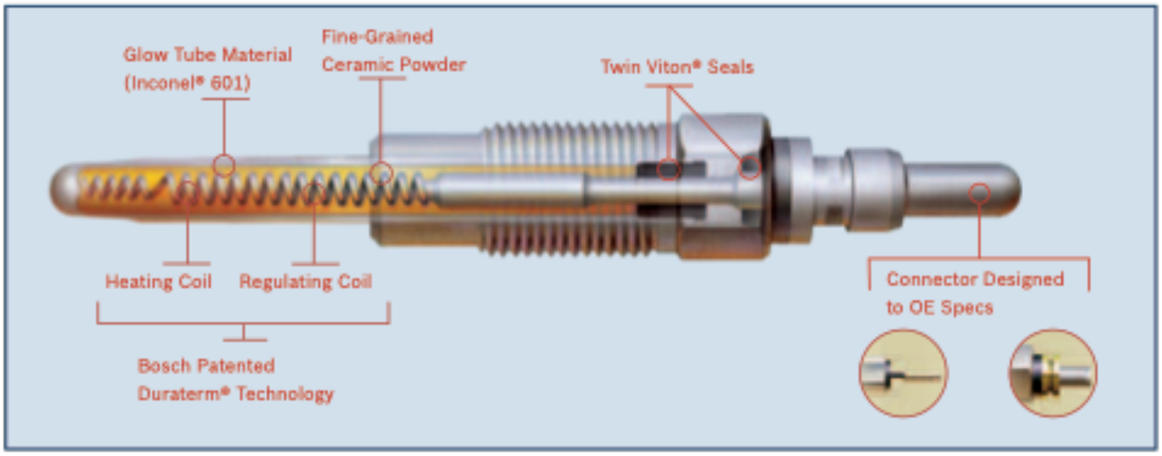
Appendix N Datasheets

Bosch Glow Plugs

Technical and Sales Information

Question 2

What sets Bosch Glow Plugs apart from other brands?



Answer

Bosch, a worldwide leader in diesel fuel injection innovation engineers and manufactures glow plugs to withstand the rigorous demands of today's diesel engines.

Feature	Benefit
Bosch patented Duraterm® technology*	Reaches higher temperature more quickly for fast engine start-up
Inconel® 601 glow tube material	Resists corrosion and vibration for long service life
Fine-grained ceramic insulating powder	Provides superior electrical insulation and high thermal conductivity
Twin Viton® seals	Protect coils from exhaust gas damage for long life
Connectors designed to OE specifications	Deliver precise fit and easy installation

Viton® is a registered trademark of DuPont Dow Elastomers LLC. Inconel® is a registered trademark of Inco Alloys International, Inc.

*Available for the majority of diesel car and light truck applications. Other applications employ standard glow plug technology per OE specifications.

†The post-glow feature allows the glow plug to remain active for up to three minutes after the vehicle has started.

page 4

Appendix O Thermocouple Data Sheets

A

Ready-Made Insulated Thermocouples

Convenient Packages of 5

5SRTC/5LRTC Series 5-Pack

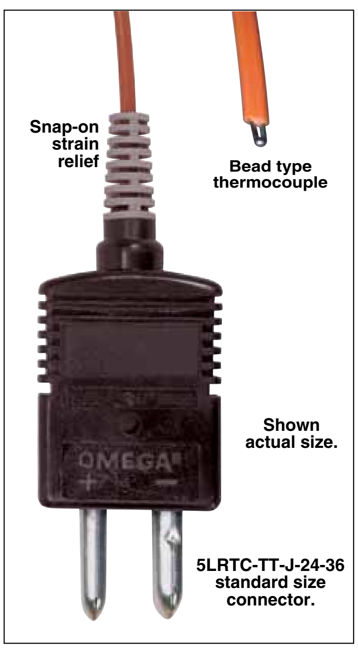
- Available from Stock in Convenient 5-Packs
- NIST Calibration Available
- PFA Insulated Wire has Max Service Temp of 260°C (500°F)
- Glass Braid Insulated Wire has Max Service Temp of 480°C (900°F)
- Kapton® Insulated Wire has Max Service Temp of 260°C (500°F)
- Available in 1 and 2 m (40 and 80") Lengths
- Max Service Temp for Connector Body 220°C (425°F)

Custom Lengths, Insulations, and Configurations Available

Miniature Size

Model Number ANSI Color Code	AWG Gage	Diameter mm (inch)	Insulation
5SRTC-GG-(*)-20-(**)	20	0.81 (0.032)	Glass Braid
5SRTC-GG-(*)-24-(**)	24	0.51 (0.020)	Glass Braid
5SRTC-GG-(*)-30-(**)	30	0.25 (0.010)	Glass Braid
5SRTC-TT-(*)-20-(**)	20	0.81 (0.032)	PFA
5SRTC-TT-(*)-24-(**)	24	0.51 (0.020)	PFA
5SRTC-TT-(*)-30-(**)	30	0.25 (0.010)	PFA
5SRTC-TT-(*)-36-(**)	36	0.13 (0.005)	PFA
5SRTC-TT-(*)-40-(**)	40	0.076 (0.003)	PFA
5SRTC-KK-(*)-20-(**)	20	0.81 (0.032)	Kapton
5SRTC-KK-(*)-24-(**)	24	0.51 (0.020)	Kapton
5SRTC-KK-(*)-30-(**)	30	0.25 (0.010)	Kapton

** Insert calibration **J, K, T,** or **E.** ** Specify length, insert **"36"** for 1 m or **"72"** for 2 m length.*
***Note:** Add cost per additional 300 mm (1') per package of 5 on GG or TT wire.*
On KK wire add cost per additional 1 foot per package.
***Ordering Example: 5SRTC-TT-K-36-72,** 5-pack of Type K thermocouples with 2 m (80") of 36 AWG PFA insulated wire and a molded mini connector with snap-on strain relief.*



Standard Size

To Order

Model Number ANSI Color Code	AWG Gage	Diameter mm (inch)	Insulation
5LRTC-GG-(*)-20-(**)	20	0.81 (0.032)	Glass Braid
5LRTC-GG-(*)-24-(**)	24	0.51 (0.020)	Glass Braid
5LRTC-TT-(*)-20-(**)	20	0.81 (0.030)	PFA
5LRTC-TT-(*)-24-(**)	24	0.51 (0.020)	PFA
5LRTC-KK-(*)-20-(**)	20	0.81 (0.032)	Kapton
5LRTC-KK-(*)-24-(**)	24	0.51 (0.020)	Kapton

** Insert calibration **J, K, T,** or **E.** ** Specify length, insert **"36"** for 1 m or **"72"** for 2 m length.*
***Note:** Add cost per additional 300 mm (1') per package of 5 on GG or TT wire.*
On KK wire add cost per additional 300 mm (1') per package.
***Ordering Example: 5LRTC-TT-K-20-72,** 5-pack of standard size thermocouples with 2 m (80") of 20 AWG PFA insulated wire.*

Ready-Made Insulated Thermocouples

with Standard or Miniature Size Spool Caddies

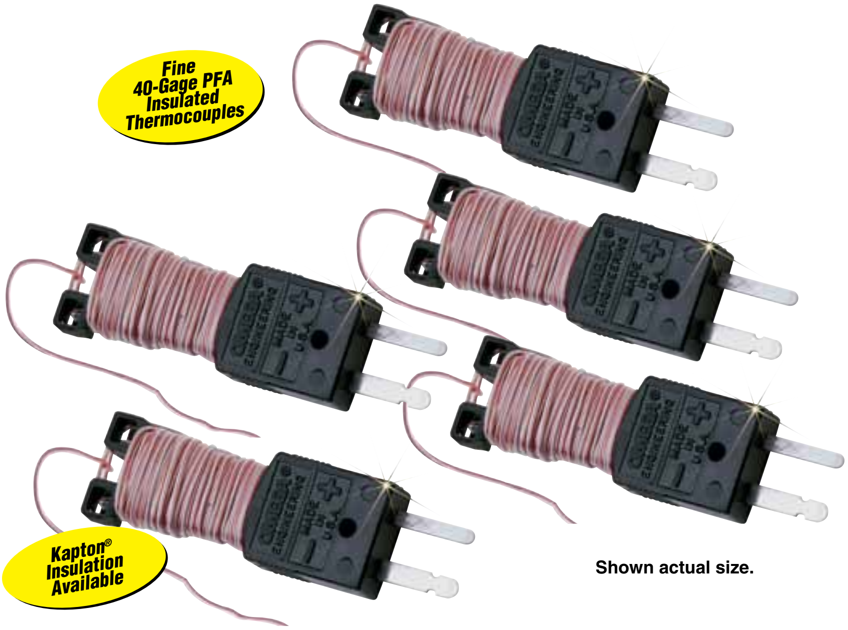
Custom Lengths, Insulations, and Configurations Available!

5SC/5LSC 5-Pack

MEETS OR EXCEEDS SPECIAL LIMITS OF ERROR (SLE) AND EN 60584-2: Tolerance Class 1

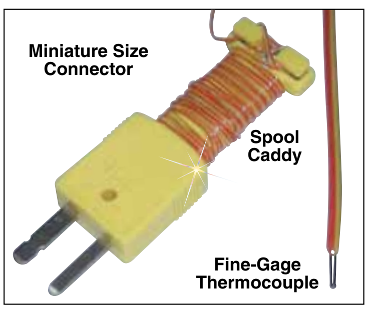
- Available from Stock in Convenient 5-Packs
- NIST Calibration Available
- Type J, K, T, and E Thermocouples
- Glass Braid Insulation Has Max Service Temp of 480°C (900°F)
- PFA Insulation Has Max Service Temp of 260°C (500°F)
- Kapton® Insulation Has Max Service Temp of 260°C (500°F)
- Stocked in 1 and 2 m (40 and 80") Lengths†
- Max Service Temp for Connector Body and Spool Caddy: 220°C (425°F)

Fine 40-Gage PFA Insulated Thermocouples

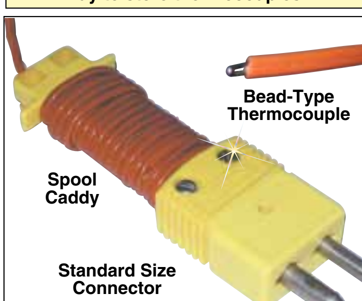


Kapton® Insulation Available

Shown actual size.



Spool caddy provides a convenient way to store thermocouples.



Both connectors shown smaller than actual size.

Miniature SMP Spool Caddy Thermocouples

To Order			
Model Number ANSI Color Code**	**AWG Gage**	**Diameter mm (inch)**	**Insulation**
5SC-GG-(*)-30-(**)	30	0.25 (0.010)	Glass Braid
5SC-TT-(*)-30-(**)	30	0.25 (0.010)	PFA
5SC-TT-(*)-36-(**)	36	0.13 (0.005)	PFA
5SC-TT-(*)-40-(**)	40	0.076 (0.003)	PFA
5SC-KK-(*)-30-(**)	30	0.25 (0.010)	Kapton

Standard OST Spool Caddy Thermocouples

Model Number ANSI Color Code	AWG Gage	Diameter mm (inch)	Insulation
5LSC-GG-(*)-20-(**)	20	0.81 (0.032)	Glass Braid
5LSC-GG-(*)-24-(**)	24	0.51 (0.020)	Glass Braid
5LSC-TT-(*)-20-(**)	20	0.81 (0.030)	PFA
5LSC-TT-(*)-24-(**)	24	0.51 (0.020)	PFA
5LSC-KK-(*)-20-(**)	20	0.81 (0.032)	Kapton
5LSC-KK-(*)-24-(**)	24	0.51 (0.020)	Kapton

** Insert calibration **J, K, T** or **E**. ** Specify length: insert **"36"** for 1 m or **"72"** for 2 m length.*
† Consult Sales for additional lengths.
***Note:** Add cost per additional 300 mm (1') per package of 5 for GG or TT wire.*
For KK wire add cost per additional 300 mm (1') per package.
***Ordering Examples: 5SC-TT-K-36-72,** 5-pack of Type K mini SMP spool caddy thermocouples with 2 m (80") 36 AWG PFA insulated wire.*
***5LSC-GG-K-20-72,** 5-pack of Type K standard size spool caddy thermocouples with 2 m (80") 20 AWG glass braid insulated wire.*

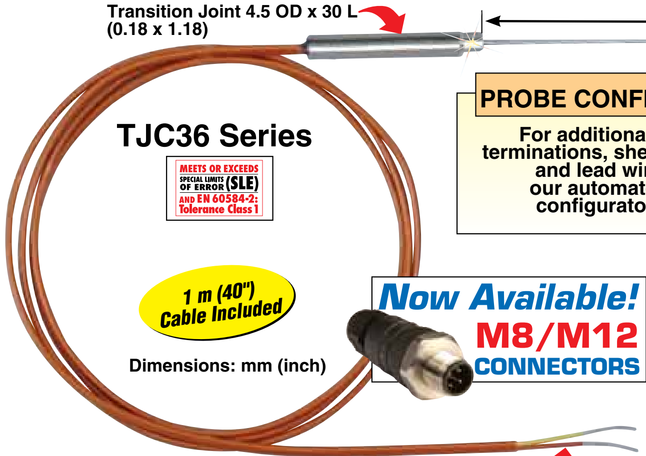
A

Compact Transition Joint Probes

Where Space is Limited PFA Insulated Lead Wire

Transition Joint 4.5 OD x 30 L (0.18 x 1.18)

150 or 300 mm (6 or 12") Lengths



TJC36-CASS-032U-12, shown smaller than actual size.

Stripped leads standard

PROBE CONFIGURATOR

For additional cold-end terminations, sheath materials, and lead wires, visit our automated probe configurator online.

Tip shown actual size.

Now Available!
M8/M12
CONNECTORS

- 304 SS, 310 SS, 316 SS, 321 SS and Inconel® 600 in Stock
- 24 AWG Stranded for All Probes
- Transition Joint Dia. of 4.5 mm (0.177")
- Available with Super OMEGACLAD® XL Compacted Mineral Insulation Cable for Long-Lasting Performance in Harsh Conditions

To Order

Calibration ANSI Code	Sheath Material	Sheath Dia. mm (in)	Upper Temp Guidelines °C (°F) T/C Junction	Model No. *Specify Junction (G)rounded, (E)xposed, or (U)ngrounded. **Probe Length 150 mm (6"), 300 mm (12"), 450 mm (18") in Stock
K CHROMEGA®-ALOMEGA®	304 SS	0.25 (0.010)	500 (932)	TJC36-CASS-010(*)-(**)
	304 SS	0.50 (0.020)	700 (1290)	TJC36-CASS-020(*)-(**)
	304 SS	0.80 (0.032)	700 (1290)	TJC36-CASS-032(*)-(**)
	304 SS	1.00 (0.040)	700 (1290)	TJC36-CASS-040(*)-(**)
	304 SS	1.59 (0.062)	920 (1690)	TJC36-CASS-062(*)-(**)
	INC 600	0.25 (0.010)	500 (932)	TJC36-CAIN-010(*)-(**)
	INC 600	0.50 (0.020)	700 (1290)	TJC36-CAIN-020(*)-(**)
	INC 600	0.80 (0.032)	700 (1290)	TJC36-CAIN-032(*)-(**)
	INC 600	1.00 (0.040)	700 (1290)	TJC36-CAIN-040(*)-(**)
	INC 600	1.59 (0.062)	920 (1690)	TJC36-CAIN-062(*)-(**)
	XL	0.25 (0.010)	600 (1112)	TJC36-CAXL-010(*)-(**)
	XL	0.50 (0.020)	800 (1472)	TJC36-CAXL-020(*)-(**)
	XL	0.80 (0.032)	800 (1472)	TJC36-CAXL-032(*)-(**)
	XL	1.00 (0.040)	800 (1472)	TJC36-CAXL-040(*)-(**)
	XL	1.59 (0.062)	1038 (1900)	TJC36-CAXL-062(*)-(**)
J IRON-CONSTANTAN	304 SS	0.25 (0.010)	260 (500)	TJC36-ICSS-010(*)-(**)
	304 SS	0.50 (0.020)	260 (500)	TJC36-ICSS-020(*)-(**)
	304 SS	0.80 (0.032)	260 (500)	TJC36-ICSS-032(*)-(**)
	304 SS	1.00 (0.040)	260 (500)	TJC36-ICSS-040(*)-(**)
	304 SS	1.59 (0.062)	440 (825)	TJC36-ICSS-062(*)-(**)
T COPPER-CONSTANTAN	304 SS	0.50 (0.020)	260 (500)	TJC36-CPSS-020(*)-(**)
	304 SS	0.80 (0.032)	260 (500)	TJC36-CPSS-032(*)-(**)
	304 SS	1.00 (0.040)	260 (500)	TJC36-CPSS-040(*)-(**)
	304 SS	1.59 (0.062)	260 (500)	TJC36-CPSS-062(*)-(**)

** Specify junction type: **E** (Exposed), **G** (Grounded) or **U** (Ungrounded). ****** Specify length in inches, plus additional price for length. Custom lengths also available; use additional price for length in 150 mm/6" increments.*

*For a male straight M8 plug add **"M8-S-M"** to the model number for additional cost, for a male straight M12 plug add **"M12-S-M"** to the model number for additional cost. For a male right-angled M8 plug add **"M8-R-M"** to the model number for additional cost, for a male right-angled M12 plug add **"M12-S-M"** to the model number for additional cost.*

***Ordering Example: TJC36-CASS-020G-6,** compact transition joint probe, 40" cable, Type K, 0.020" OD stainless steel sheath, 6" length, grounded junction.*